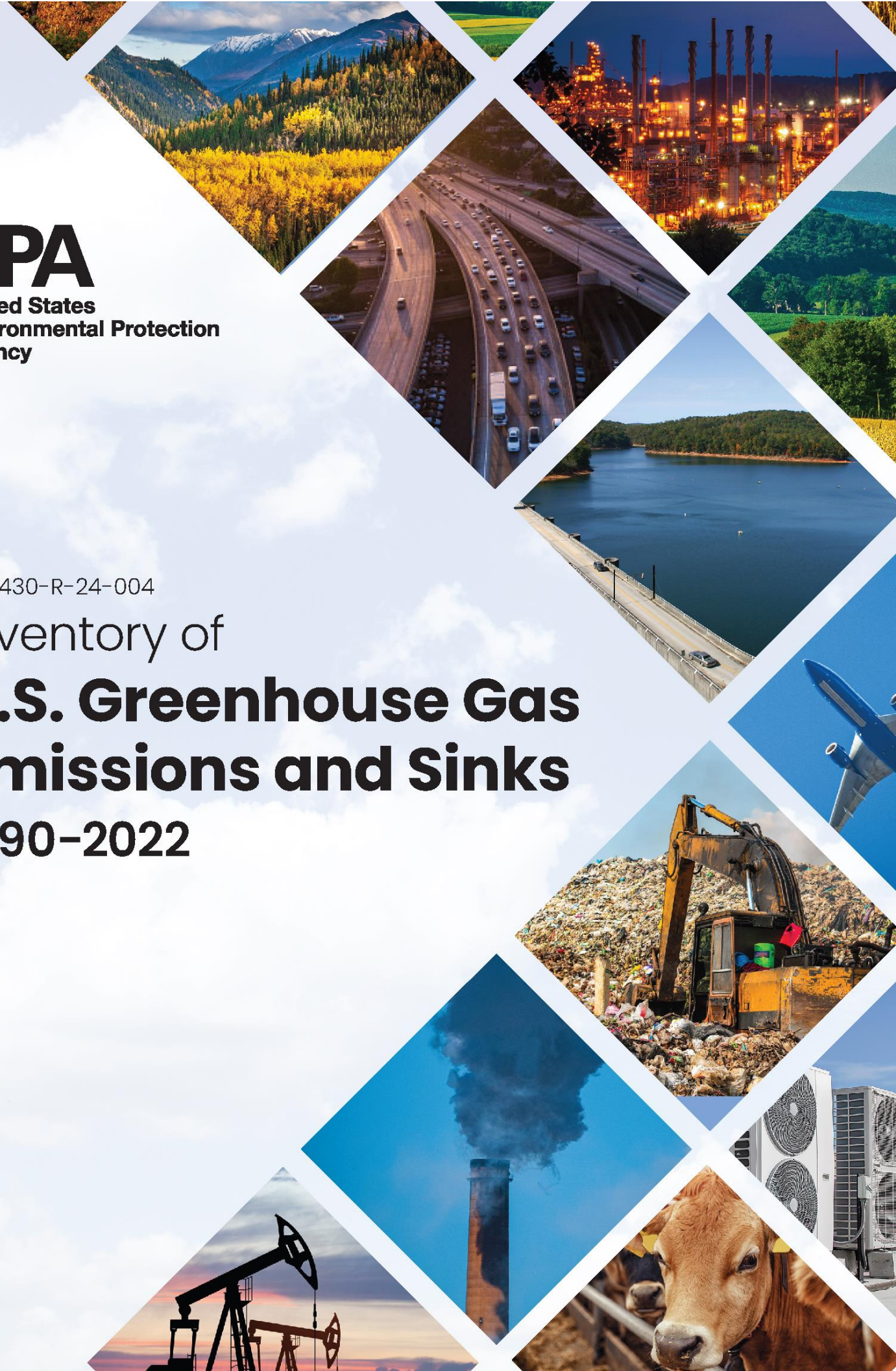


EPA

United States
Environmental Protection
Agency

EPA 430-R-24-004

Inventory of
U.S. Greenhouse Gas Emissions and Sinks
1990–2022

Front cover photo credit for cow and digester: Vanguard Renewables.

HOW TO OBTAIN COPIES

You can electronically download this document on the U.S. EPA's homepage at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

All data tables of this document for the full time series 1990 through 2022, inclusive, will be made available within 4-6 weeks after publication of the final report online at the link mentioned in the citation below.

RECOMMENDED CITATION

EPA (2024) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022. U.S. Environmental Protection Agency, EPA 430-R-24-004. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

FOR FURTHER INFORMATION

Contact Ms. Mausami Desai, Environmental Protection Agency, (202) 304–8932, desai.mausami@epa.gov,

or Mr. Vincent Camobreco, Environmental Protection Agency, (202) 617–6678, camobreco.vincent@epa.gov.

For more information regarding climate change and greenhouse gas emissions, see the EPA web site at https://www.epa.gov/ghgemissions.

Acknowledgments

The Environmental Protection Agency would like to acknowledge the many individual and organizational contributors to this document, without whose efforts this report would not be complete. Although the complete list of researchers, government employees, and consultants who have provided technical and editorial support is too long to list here, EPA would like to thank some key contributors and reviewers whose work has significantly improved this year's report.

Within EPA's Office of Atmospheric Protection (OAP), development and compilation of emissions from fuel combustion was led by Vincent Camobreco. Sarah Roberts (EPA Office of Transportation and Air Quality (OTAQ)) directed the work to compile estimates of emissions from mobile sources. Work on fugitive methane emissions from the Energy sector was directed by Julie Powers, Melissa Weitz and Chris Sherry. Development and compilation of emissions estimates for the Waste sector were led by Lauren Aepli and Mausami Desai. John Steller and Kenna Rewcastle directed work to compile estimates for the Agriculture and the Land Use, Land-Use Change, and Forestry chapters with support from Jake Beaulieu and Alex Hall (EPA Office of Research and Development (ORD) on compiling the inventories for CO_2 and CH_4 associated with flooded lands. Development and compilation of Industrial Processes and Product Use (IPPU) CO_2, CH_4, and N_2O emissions was directed by Amanda Chiu and Vincent Camobreco. Development and compilation of emissions of HFCs, PFCs, SF_6, and NF_3 from the IPPU sector was directed by Deborah Ottinger, Dave Godwin, and Stephanie Bogle. Cross-cutting work was directed by Mausami Desai. We thank Bill Irving for general advice, guidance, and cross-cutting review.

Other EPA offices and programs also contributed data, analysis, and technical review for this report. OAP's Greenhouse Gas Reporting Program staff facilitated aggregation and review of facility-level data for use in the Inventory, in particular aggregation of confidential business information data. The Office of Air Quality Planning and Standards (OAQPS) with contributions from OTAQ provided analysis for precursor estimates and review for several of the source categories (i.e., natural gas and petroleum systems) included in this report. ORD conducted field research and developed estimates associated with flooded lands. The Office of Land and Emergency Management (OLEM) also contributed analysis and research.

The Energy Information Administration (EIA) and the Department of Energy (DOE) contributed invaluable data and analysis on numerous energy-related topics. William Sanchez and Kevin Nakolan at EIA provided annual energy data that are used in fossil fuel combustion estimates. We also thank Chris Tremper, Soudeh Motamedi, and Ashley Ruocco at the Department of Energy for providing data and information on emissions of SF_6 and PFCs from Other Product Use. Other government agencies have contributed data as well, including the U.S. Geological Survey (USGS), the Federal Highway Administration (FHWA), the Department of Transportation (DOT), the Bureau of Transportation Statistics (BTS), the Department of Commerce, the Mine Safety and Health Administration (MSHA), and the National Agricultural Statistics Service (NASS).

We thank the Department of Defense (DOD) (David Asiello, DoD and Matthew Cleaver of Leidos) for compiling the data on military bunker fuel use.

We thank the Federal Aviation Administration (FAA) (Ralph Lovinelli and Jeetendra Upadhyay) for compiling the inventory of emissions from commercial aircraft jet fuel consumption.

We thank the United States Department of Agriculture's Office of the Chief Economist (USDA-OCE) (Meg Xiarchos) and Economic Research Service (USDA-ERS) (Jeffrey Hopkins) for providing data on agricultural energy use.

We thank the U.S. Forest Service (USFS) (Grant Domke, Brian Walters, James Smith, and Courtney Giebink) for compiling the inventories for CO_2, CH_4, and N_2O fluxes associated with forest land.

We thank the Department of Agriculture's Agricultural Research Service (USDA-ARS) (Stephen Del Grosso) and the Natural Resource Ecology Laboratory and Department of Statistics at Colorado State University (CSU) (Stephen Ogle, Bill Parton, Shannon Spencer, Alisa Keyser, Lauren Hoskovec, Ram Gurung, Ryan Scheiderer, Veronica Thompson, Stephen Williams, and Guhan Dheenadayalan Sivakami) for compiling the inventories for CH_4 emissions, N_2O emissions, and CO_2 fluxes associated with soils in croplands, grasslands and settlements.

We thank the National Oceanic and Atmospheric Administration (NOAA) (Nate Herold, Ben DeAngelo and Meredith Muth), Silvestrum Climate Associates (Stephen Crooks, Lisa Schile Beers, Rebeca Brenes), the Smithsonian Environmental Research Center (J. Patrick Megonigal, James Holmquist, Jaxine Wolfe and Meng Lu), and Florida International University (Tiffany Troxler) as well as members of the U.S. Coastal Wetland Carbon Working Group for compiling inventories of land use change, soil carbon stocks and stock change, CH_4 emissions, and N_2O emissions from aquaculture in coastal wetlands. We also thank NOAA's Global Monitoring Lab (Stephen Montzka and Lei Hu) for information on atmospheric measurements and derived emissions of HFCs and SF_6.

We thank Marian Martin Van Pelt, Leslie Chinery, Alexander Lataille, Mollie Carroll, and the full Inventory team at ICF including Diana Pape, Robert Lanza, Mollie Averyt, Larry O'Rourke, Ted Atwood, Skyler Brown, Deborah Harris, Rebecca Ferenchiak, Fiona Wissell, Bikash Acharya, Sophie Johnson, Kyle Herdegen, Hazelle Tomlin, Lou Browning, Johanna Garfinkel, Anna Cliche, Valerie Hammer, Mallory Giesie, David Landolfi, Emily Carr, Georgia Kerkezis, Isabella Scornaienchi, Katie O'Malley, Maris Welch, Emily Adkins, Zeyu Hu, Alex Da Silva, Sneha Balakrishnan, Kenny Yerardi, Leah Hartung, Molly Rickles, Seth Hartley and Ajo Rabemiarisoa for technical support in compiling synthesis information across the report and preparing many of the individual analyses for specific report chapters including fluorinated emissions and fuel combustion.

We thank Eastern Research Group for their analytical support. Deborah Bartram, Kara Edquist and Madison Eaton support the development of emissions estimates for wastewater. Kara Edquist, Cortney Itle, Amber Allen, Spencer Sauter, Sarah Wagner, and Madison Eaton support the development of emission estimates for manure management, enteric fermentation, peatlands (included in wetlands remaining wetlands*)*, and landfilled yard trimmings and food scraps (included in settlements remaining settlements). Brandon Long, Gopi Manne, and Marty Wolf support the development of estimates for natural gas and petroleum systems. Gopi Manne and Tara Stout support the development of emission estimates for coal mine methane.

Finally, we thank the RTI International team: Kate Bronstein, Emily Thompson, Jeff Coburn, and Keith Weitz for their analytical support in development of the estimates of emissions from landfills; Melissa Icenhour, Michael Laney, David Randall, Gabrielle Raymond, Karen Schaffner, Riley Vanek, Ricky Strott, Libby Robinson, Matt Hakos, and Jeremy Kaelin for their analytical support in development of IPPU CO_2, CH_4, and N_2O emissions; Karen Schaffner and Haley Key for their analytical support in the development of the estimates of emissions from fluorochemical production; and Tiffany Moore and Matt Hakos for their analytical support on disaggregating industrial sector fossil fuel combustion emissions.

Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to fulfill annual existing commitments under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). National greenhouse gas (GHG) inventory reports are to be submitted each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The draft document was announced via Federal Register Notice and published for a 30-day comment period on the EPA Greenhouse Gas Emissions and Removals web site from February 14 through March 15, 2024, and comments received during the public review period are posted to the docket EPA-HQ-OAR-2024-0004. Comments received after the closure of the public comment period will be considered for the next edition of this annual report. Responses to comments are typically posted to EPA's website 2-4 weeks following publication of the final report in April 2024.

Table of Contents

List of Tables, Figures, Boxes, and Equations

Tables

Figures

Boxes

Equations

Executive Summary

An inventory that identifies and quantifies a country's anthropogenic[1] sources and sinks of greenhouse gas emissions and removals is essential for addressing climate change. This *Inventory* adheres to both (1) a comprehensive and detailed set of methodologies for estimating national sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent format that enables Parties to the Paris Agreement and United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different greenhouse gases emissions and removals to climate change.

The United States is party to both the 1992 UNFCCC and the 2015 Paris Agreement. The Paris Agreement set a global temperature goal – holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C – that articulates with greater precision States' views on what is necessary to meet the UNFCCC's objective of "stabiliz[ing] … greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[2]

The United States is committed to submitting a national inventory of anthropogenic emission sources and removals by sinks of greenhouse gases by April 15 of each year. The United States has prepared this report, in conjunction with Common Reporting Tables (CRTs) that accompany this report, consistent with its obligations under those agreements.

This Executive Summary provides the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2022. The structure of this report is consistent with requirements under the Paris Agreement and the UNFCCC on national greenhouse gas inventory reporting, as discussed in Box ES-1. Throughout this report, emission and sink estimates are grouped into five reporting sectors (i.e., chapters): Energy, IPPU, Agriculture, Land Use, Land-Use Change, and Forestry (LULUCF), and Waste. In describing trends (Chapter 2), emissions and sinks are also summarized according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. See Box 2-1 for more information on how economic sectors are defined.

Box ES-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines)* and, where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories

[1] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[2] See Paris Agreement, Article 2.1(a); UNFCCC, Article 2.

under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in this *Inventory* does not preclude alternative examinations (e.g., economic sectors). Rather, this *Inventory* presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP), which is complementary to the U.S. Inventory.[3] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[4] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for reporting year 2011.[5] Methodologies used in EPA's GHGRP are consistent with the 2006 IPCC Guidelines. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and removals (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors), it is an important input to the calculations of national-level emissions in this *Inventory*.

The GHGRP dataset provides not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and subcategories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. See Annex 9 for more information on specific uses of GHGRP data in the Inventory (e.g., use of Subpart W data in compiling estimates for natural gas systems).

ES.1 Background Information

Greenhouse gases absorb infrared radiation, trapping heat in the atmosphere and making the planet warmer. The most important greenhouse gases directly emitted by human activities include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several fluorine-containing halogenated substances (HFCs, PFCs, SF_6 and NF_3). Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2022, concentrations of these greenhouse gases have increased globally by 49.5, 161.9, and 24.3 percent, respectively (IPCC 2013; NOAA/ESRL 2024a, 2024b, 2024c). This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States.

[3] On October 30, 2009, EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[4] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

[5] See https://ccdsupport.com/confluence/pages/viewpage.action?pageId=322699300.

Global Warming Potentials

The IPCC developed the global warming potential (GWP) concept to compare the ability of a greenhouse gas to trap heat in the atmosphere relative to another gas. A GWP is a quantified measure of the relative globally averaged radiative forcing impacts of emissions of a particular greenhouse gas over time. The GWP of a greenhouse gas is defined as the ratio of the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram of the gas, relative to that of the reference gas CO_2 (IPCC 2021); therefore, CO_2-equivalent emissions are provided in million metric tons of CO_2 equivalent (MMT CO_2 Eq.) for non-CO_2 greenhouse gases.[6,7] All estimates are provided throughout the main report in both CO_2 equivalents and unweighted units, while estimates for all gases in this Executive Summary are presented in units of MMT CO_2 Eq. Emissions by gas in unweighted mass kilotons are also provided in the Trends chapter and individual sector chapters of this report, and in the CRTs that are included in the submission to the UNFCCC.

Recent decisions under the Paris Agreement[8] and the UNFCCC[9] require Parties to use 100-year GWP values from the IPCC *Fifth Assessment Report* (AR5) for calculating CO_2-equivalents in their national reporting (IPCC 2013) by the end of 2024. This reflects updated science and ensures that national greenhouse gas inventories reported by all nations are comparable. This report reflects CO_2-equivalent greenhouse gas emission totals using 100-year AR5 GWP values. A comparison of emission values with the IPCC *Sixth Assessment Report* (AR6) (IPCC 2021) values can be found in Annex 6.1 of this report. The 100-year GWP values used in this report are listed below in Table ES-1.

Table ES-1: Global Warming Potentials (100-Year Time Horizon) Used in this Report

Gas	GWP
CO_2	1
CH_4[a]	28
N_2O	265
HFCs	up to 12,400
PFCs	up to 11,100
SF_6	23,500
NF_3	16,100
Other Fluorinated Gases	See Annex 6

[a] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to production of CO_2 is not included. See Annex 6 for additional information.
Source: IPCC (2013).

[6] Carbon comprises 12/44 of carbon dioxide by weight.

[7] One million metric ton is equal to 10^{12} grams or one teragram.

[8] See Annex to decision 18/CMA.1, available online at https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[9] See paragraphs 1 and 2 of the decision on common metrics adopted at the 27th UNFCCC Conference of Parties (COP27), available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

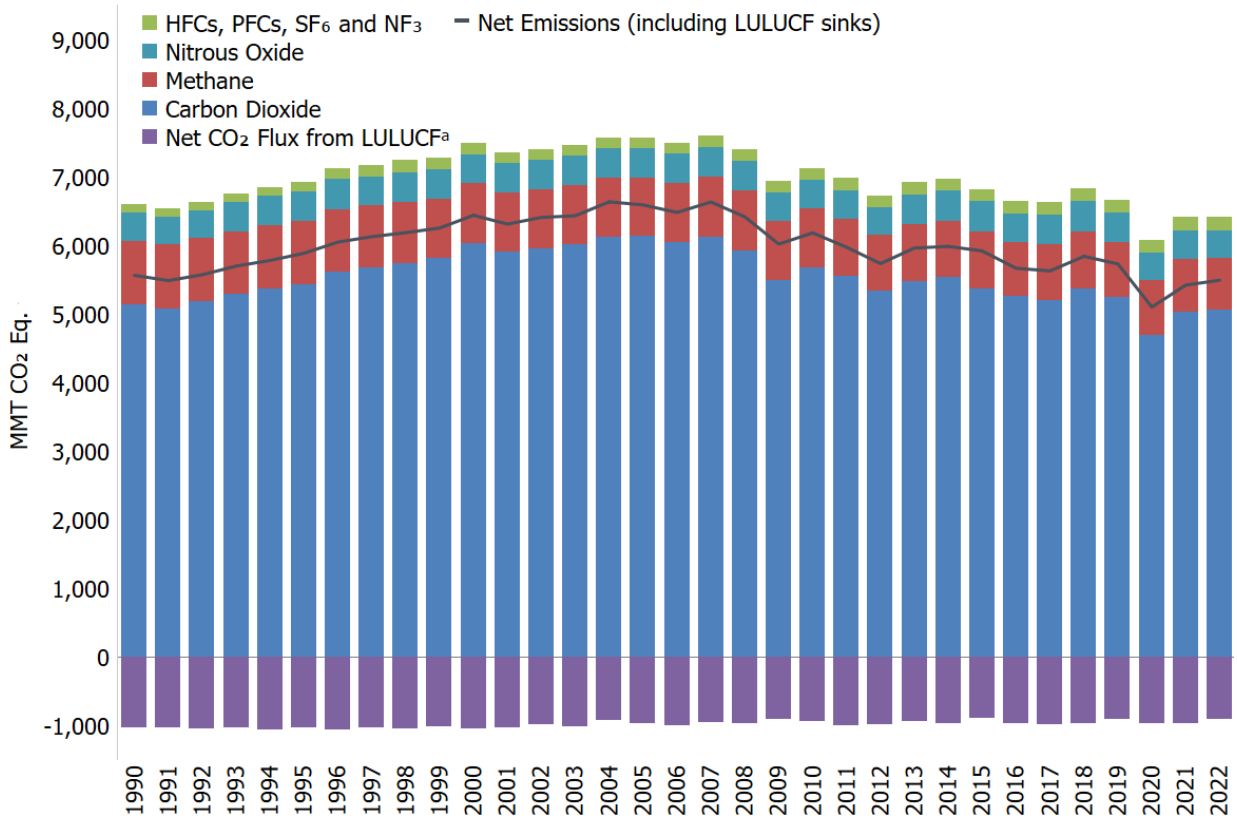
ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2022, total gross U.S. greenhouse gas emissions were 6,343.2 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).[10] Total gross U.S. emissions decreased by 3.0 percent from 1990 to 2022, down from a high of 15.2 percent above 1990 levels in 2007. Gross emissions increased from 2021 to 2022 by 0.2 percent (14.4 MMT CO_2 Eq.). Net emissions (including sinks) were 5,489.0 MMT CO_2 Eq. in 2022. Overall, net emissions increased by 1.3 percent from 2021 to 2022 and decreased by 16.7 percent from 2005 levels as shown in Table ES-2. Between 2021 and 2022, the increase in total greenhouse gas emissions was driven largely by an increase in CO_2 emissions from fossil fuel combustion across most end-use sectors due in part to increased energy use from the continued rebound of economic activity after the height of the COVID-19 pandemic. In 2022, CO_2 emissions from fossil fuel combustion increased by 1.0 percent relative to the previous year and were 1.1 percent below emissions in 1990. Carbon dioxide emissions from natural gas use increased by 5.2 percent (84.8 MMT CO_2 Eq.) from 2021, while CO_2 emissions from coal consumption decreased by 6.1 percent (58.6 MMT CO_2 Eq.) from 2021 to 2022. The increase in natural gas consumption and associated emissions in 2022 is observed across all sectors except U.S. Territories, while the coal decrease is due to reduced use in the electric power sector. Emissions from petroleum use also increased by 0.9 percent (19.0 MMT CO_2 Eq.) from 2021 to 2022. Carbon sequestration from the Land Use, Land-Use Change, and Forestry (LULUCF) sector offset 14.5 percent of total emissions in 2022.

Figure ES-1 and Figure ES-2 illustrate the overall trends in total U.S. emissions by gas and annual percent changes, and Table ES-2 provides information on trends in gross U.S. greenhouse gas emissions and sinks for 1990 through 2022. Unless otherwise stated, all tables and figures provide total gross emissions and exclude the greenhouse gas fluxes from the LULUCF sector. For more information about the LULUCF sector, see Section ES-3.

[10] The gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF.

Figure ES-1: U.S. Greenhouse Gas Emissions and Sinks by Gas



[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	5,131.6	6,126.9	5,362.2	5,234.5	4,689.0	5,017.2	5,053.0	-1.5%
CH_4 (excludes LULUCF sources)[a]	871.7	795.4	771.5	754.3	735.3	720.5	702.4	-19.4%
N_2O (excludes LULUCF sources)[a]	408.2	419.2	439.5	416.4	391.2	398.2	389.7	-4.5%
HFCs	47.7	121.7	163.9	168.2	170.3	177.0	182.8	282.9%
PFCs	39.5	10.2	7.4	7.3	6.6	6.3	6.7	-83.1%
SF_6	37.9	20.2	7.6	8.4	8.1	8.5	7.6	-80.0%
NF_3	0.3	1.0	0.7	1.1	1.3	1.1	1.1	238.3%
Total Gross Emissions (Sources)[a]	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Emissions[b]	58.0	68.9	62.8	58.0	68.4	72.9	67.6	16.5%
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4	10.0%
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1	88.3%
LULUCF Carbon Stock Change[c]	(1034.7)	(976.6)	(978.3)	(921.6)	(972.8)	(983.4)	(921.8)	-10.9%
LULUCF Sector Net Total[d]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] Gross emissions totals do not include CH_4 and N_2O emissions from LULUCF. LULUCF CH_4 and N_2O emissions are included in net emission totals.

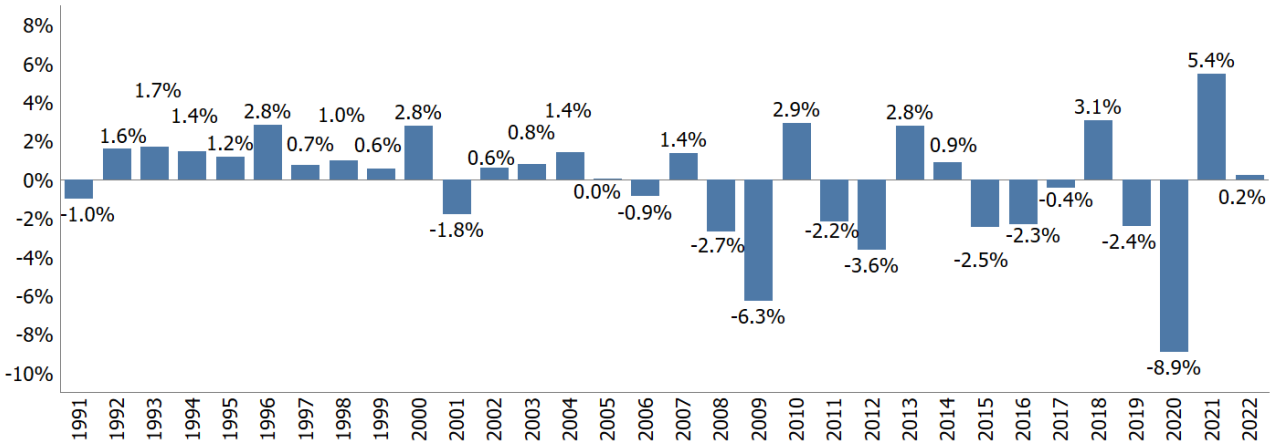
[b] LULUCF emissions subtotal of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[c] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[d] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) are emissions presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Figure ES-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions and Sinks Relative to the Previous Year

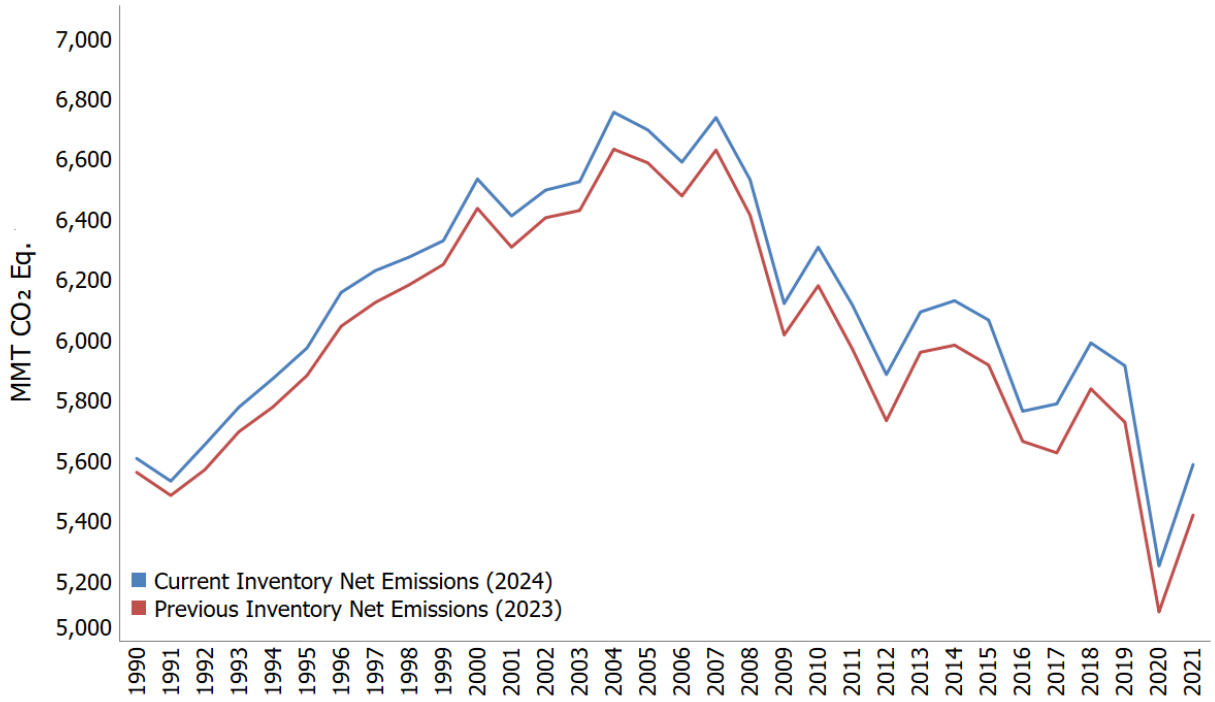


Improvements and Recalculations Relative to the Previous Inventory

Each year, some emission and removal estimates in the *Inventory* are recalculated and revised to incorporate improved methods and/or data. The most common reason for recalculating U.S. greenhouse gas emission estimates is to update recent historical data. Changes in historical data are generally the result of changes in data supplied by other U.S. government agencies or organizations, as they continue to make refinements and improvements. These improvements are implemented consistently across the previous *Inventory's* time series, as necessary, (i.e., 1990 to 2021) to ensure that the trend is accurate.

Collectively, all methodological changes and historical data updates made in the current *Inventory* resulted in an annual average decrease of 114.8 MMT CO_2 Eq. (1.9 percent) for net emissions.

Figure ES-3: Impacts of Recalculations on Net Emissions



Below are categories with methodological and data-related recalculations resulting in an average change of greater than 2.0 MMT CO_2 Eq. over the time series.

- Forest land remaining forest land: changes in forest carbon stocks (CO_2)
- Land converted to grassland: changes in all ecosystem carbon stocks (CO_2)
- Land converted to cropland: changes in all ecosystem carbon stocks (CO_2)
- Grassland remaining grassland: changes in all ecosystem carbon stocks (CO_2)
- Non-energy use of fuels (CO_2)
- Land converted to settlements: changes in all ecosystem carbon stocks (CO_2)
- Fluorochemical production (HFCs)
- Fossil fuel combustion (CO_2)
- Cropland remaining cropland: changes in all ecosystem carbon stocks (CO_2)
- Agricultural Soil Management (N_2O)
- Petroleum Systems (CH_4)
- Wetlands Remaining Wetlands: changes in soil carbon stocks in coastal wetlands (CO_2)

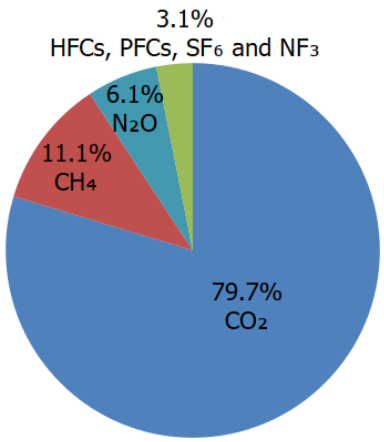
In addition, the current *Inventory* includes new categories not included in the previous *Inventory* that improve completeness of the national estimates: CO_2 emissions from ceramics production and non-metallurgical magnesia production within other process use of carbonates category, fluorinated gases from fluorochemical production other than HCFC-22 within the fluorochemical production category, and managed forest land in Hawaii and several U.S. Territories. This report also now includes SF_6 and PFCs from product uses.

In each *Inventory*, the results of all methodological changes and historical data updates and the inclusion of new sources and sink estimates are summarized in the Recalculations and Improvements chapter (Chapter 9). For more detailed descriptions of each recalculation including references for data, please see the respective source or sink category description(s) within the relevant report chapter (the Energy chapter [Chapter 3], the Industrial Processes and Product Use [IPPU] chapter [Chapter 4], the Agriculture chapter [Chapter 5], the Land Use, Land-Use Change, and Forestry [LULUCF] chapter [Chapter 6], and the Waste chapter [Chapter 7]).

Emissions and Sinks by Greenhouse Gas

Figure ES-4 illustrates the relative contribution of the greenhouse gases to total gross U.S. emissions in 2022, weighted by GWP. The primary greenhouse gas emitted by human activities in the United States is CO_2, representing 79.7 percent of total greenhouse gas emissions. The largest source of CO_2 and of overall greenhouse gas emissions is fossil fuel combustion, primarily from transportation and power generation. Methane (CH_4) emissions account for 11.1 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of wastes in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management are the major sources of N_2O emissions. Emissions of substitutes for ozone depleting substances are the primary contributor to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions are primarily attributable to electronics manufacturing, fluorochemical production, and primary aluminum production. Electrical equipment systems account for most sulfur hexafluoride (SF_6) emissions. The electronics industry and fluorochemical production are the only sources of nitrogen trifluoride (NF_3) emissions. U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in forests, trees in urban areas, agricultural soils, landfilled yard trimmings and food scraps, and coastal wetlands, which together offset 14.5 percent of gross total emissions in 2022 (as reflected in Figure ES-1). The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

Figure ES-4: 2022 Total Gross U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from the figure above.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, global carbon fluxes among these various reservoirs are roughly balanced.[11]

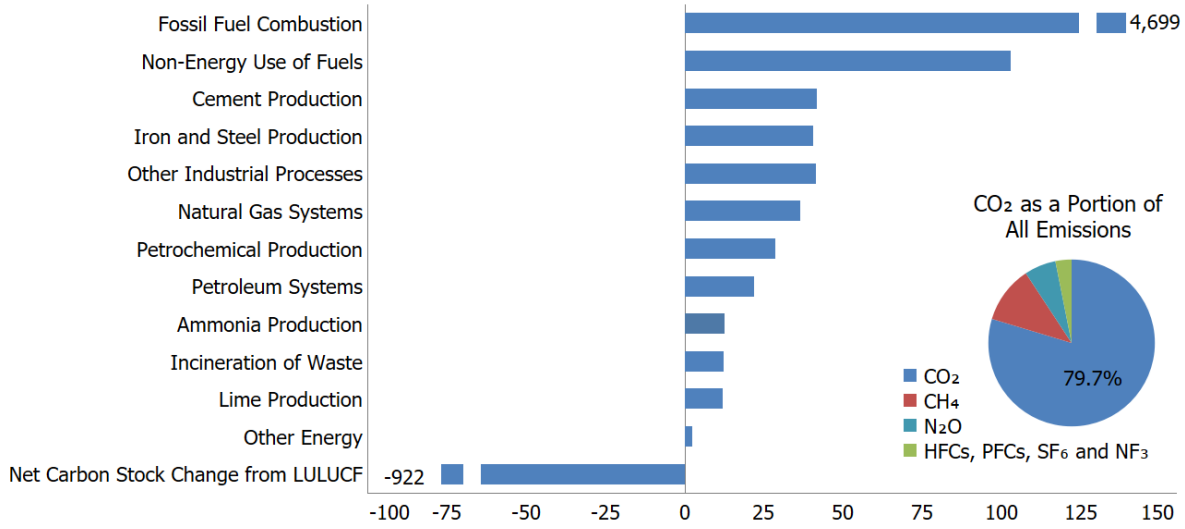
Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen 49.5 percent (IPCC 2013; NOAA/ESRL 2024a), principally due to the combustion of fossil fuels for energy. Globally, an estimated

[11] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

33,423 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2022, of which the United States accounted for approximately 14.1 percent.[12]

Overall CO_2 emissions have decreased by 1.5 percent since 1990 and increased by 0.7 percent since 2021, consistent with trends in fuel combustion emissions. Within the United States, fossil fuel combustion accounted for 93.0 percent of CO_2 gross emissions in 2022. Nationally, the transportation sector was the largest emitter of CO_2 in 2022 followed by electric power generation. There are 27 additional sources of CO_2 emissions included in the *Inventory* (see [Table 2-1 in Trends]). Although not illustrated in Table ES-4, changes in land use and forestry practices can also lead to net CO_2 emissions (e.g., through conversion of forest land to agricultural or urban use) or to a net sink for CO_2 (e.g., through net additions to forest biomass). See more on these emissions and removals in Table ES-4.

Figure ES-5: 2022 Sources of CO_2 Emissions



Note: "Other Industrial Processes" includes emissions from aluminum production, carbide production and consumption, carbon dioxide consumption, ferroalloy production, glass production, lead production, magnesium production, other process uses of carbonates, phosphoric acid production, substitution of ozone depleting substances, soda ash production, titanium dioxide production, urea consumption for non-agricultural purposes, and zinc production. "Other Energy" includes emissions from abandoned oil and gas wells and coal mining.

Between 1990 and 2022, CO_2 emissions from fossil fuel combustion decreased by 1.1 percent; emissions decreased by 18.2 percent (1,044.7 MMT CO_2 Eq.) from 2005 levels; and from 2021 to 2022, these emissions increased by 1.0 percent (45.1 MMT CO_2 Eq.).

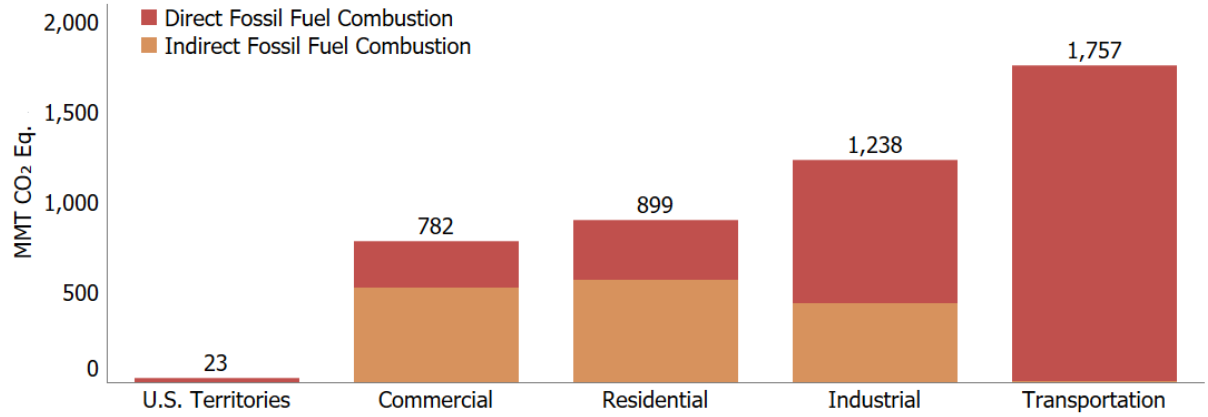
Historically, changes in emissions from fossil fuel combustion have been the driving factor affecting U.S. emission trends. Important drivers include changes in demand for energy and a general decline in the overall carbon intensity of fuels combusted for energy in recent years by non-transport sectors of the economy. Between 2019 and 2021, changes in economic activity and travel due to the COVID-19 pandemic and the subsequent recovery had significant impacts on energy use and fossil fuel combustion emissions.

The five major fuel-consuming economic sectors are transportation, electric power, industrial, residential, and commercial and are described below. Carbon dioxide emissions are produced by the electric power sector as fossil fuel is consumed to provide electricity to one of the other four economic sectors, or "end-use" sectors. In Figure

[12] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Global energy-related CO_2 emissions, 1990-2022 – Charts.* Available at: https://www.iea.org/reports/co2-emissions-in-2022 (IEA 2022).

ES-6, electric power emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity use (i.e., indirect fossil fuel combustion). Greenhouse gas emissions from the commercial and residential and industry increase substantially when indirect emissions from electricity end-use are distributed, due to the relatively large share of electricity use by buildings (e.g., heating, ventilation, and air conditioning; lighting; and appliances) and use of electricity for powering industrial machinery.

Figure ES-6: 2022 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Transportation End-Use Sector. Transportation activities accounted for 37.4 percent of U.S. CO_2 emissions from fossil fuel combustion in 2022, with the largest contributors being light-duty trucks (36.8 percent), followed by medium- and heavy-duty trucks (23.0 percent) and passenger vehicles (20.6 percent). In terms of the overall trend from 1990 to 2022, total transportation CO_2 emissions increased due largely to increased demand for travel, which was a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. While an increased demand for travel has led to generally increasing CO_2 emissions since 1990, improvements in average new vehicle fuel economy since 2005 have slowed the rate of increase of CO_2 emissions. In 2022, petroleum-based products supplied 94.3 percent of the energy consumed for transportation, primarily from gasoline consumption in automobiles and other highway vehicles (51.9 percent).

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels[13] and indirectly from the generation of electricity that is used by industry, accounted for 26.3 percent of CO_2 emissions from fossil fuel combustion in 2022. Approximately 64.7 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from the use of electricity for motors, electric furnaces, ovens, lighting, and other applications. Total direct and indirect emissions from the industrial sector have declined by 20.8 percent since 1990. This decline is due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements. From 2021 to 2022, total energy use in the industrial sector increased by 1.8 percent due to an increase in total industrial production and manufacturing output.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 19.1 and 16.6 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2022 including indirect emissions from electricity. The residential and commercial sectors relied heavily on electricity for meeting energy demands, with 62.9 and 66.9 percent, respectively, of their emissions attributable to electricity use for building -related activities such as lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Total direct and indirect emissions from the residential sector have decreased by 3.4 percent since 1990, and total direct and indirect emissions from the commercial sector have increased by 2.1 percent since 1990. From 2021 to 2022, an increase in heating degree

[13] This does not include fossil fuels used as feedstocks and reductants, which are reported under IPPU emissions.

days (7.9 percent) increased energy demand for heating in the residential and commercial sectors; also, a 4.3 percent increase in cooling degree days compared to 2021 increased demand for air conditioning in the residential and commercial sectors. Combined, this resulted in a 2.5 percent increase in residential sector energy use. From 2021 to 2022, energy use in the commercial sector increased by 4.7 percent.

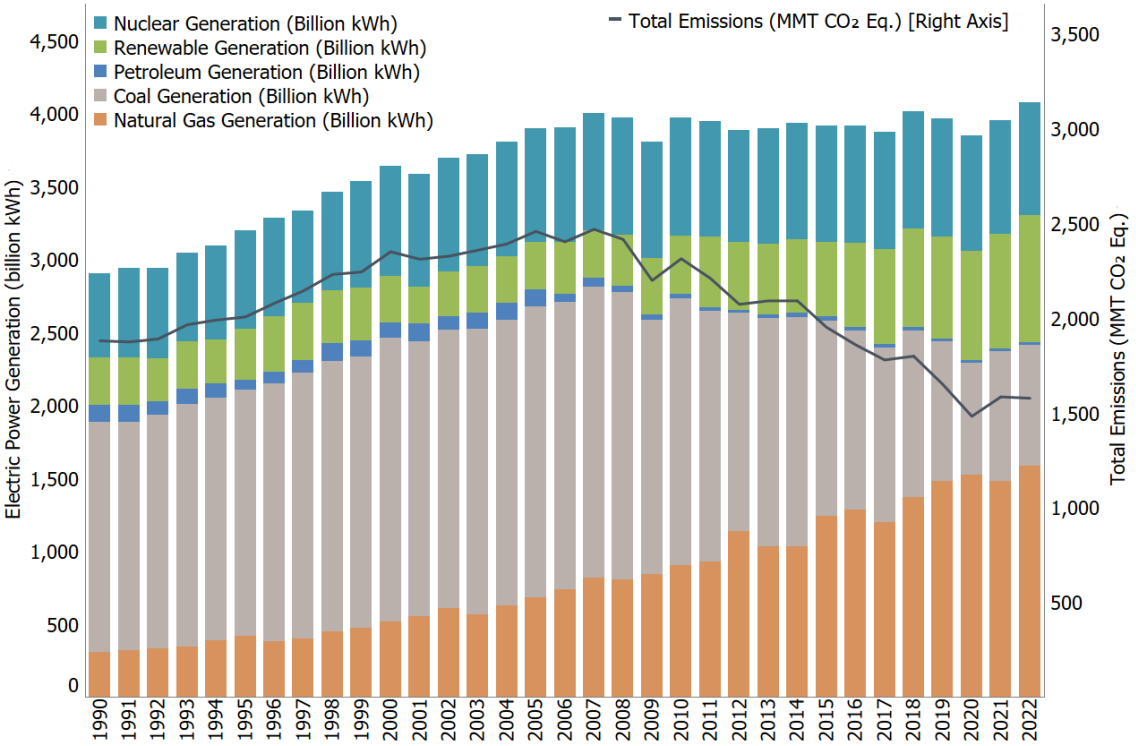
Electric Power. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators used 30.5 percent of U.S. energy from fossil fuels and emitted 32.6 percent of the CO_2 from fossil fuel combustion in 2022. The type of energy source used to generate electricity, and the mix of electric generation resources used to meet demand, are the main factors influencing emissions.[14] Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54.1 percent of generation in 1990 to 20.3 percent in 2022.[15] This corresponded with an increase in natural gas generation and non-fossil fuel renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 10.7 percent of electric power generation in 1990 and increased over the 33-year period to represent 38.8 percent of electric power generation in 2022. Wind and solar generation (in kWh) represented 0.1 percent of electric power generation in 1990 and increased over the 33-year period to represent 14.2 percent of electric power generation in 2022. Between 2021 and 2022, coal electricity generation decreased by 10.2 percent, natural gas generation increased by 4.0 percent, and renewable energy generation increased by 7.6 percent.

Across the time series, changes in electricity generation and the carbon intensity of fuels used for electric power have a significant impact on CO_2 emissions. While CO_2 emissions from fossil fuel combustion in the electric power sector have decreased by 15.8 percent since 1990, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, decreased by 27.6 percent during that same timeframe. This decoupling of the level of electric power generation and the resulting CO_2 emissions is shown in Figure ES-7.

[14] In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not included in the electricity sector totals and trends discussed in this section. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[15] Values represent electricity *net* generation from the electric power sector. See Table 7.2b Electricity Net Generation: Electric Power Sector of EIA (2024).

Figure ES-7: Electric Power Generation and Emissions



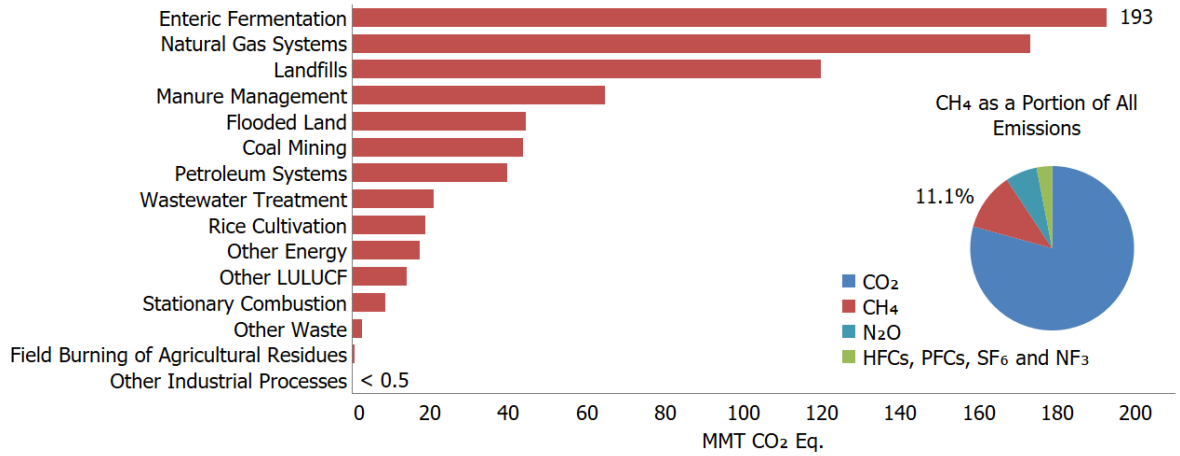
Other significant CO_2 trends included the following:

- Carbon dioxide emissions from natural gas and petroleum systems combined accounted for 1.2 percent of CO_2 emissions and 0.9 percent of total gross emissions in 2022. These emissions increased by 39.1 percent (16.4 MMT CO_2 Eq.) from 1990 to 2022. This increase is due primarily to increases in the production segment, where flaring emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time.
- Carbon dioxide emissions from iron and steel production and metallurgical coke production accounted for 0.8 percent of CO_2 and 0.6 percent of total gross emissions. Emissions decreased by 61.2 percent (64.1 MMT CO_2 Eq.) from 1990 through 2022. This decrease was primarily due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Total carbon stock change (i.e., net CO_2 removals) in the LULUCF sector decreased by 10.9 percent between 1990 and 2022. This decrease was primarily due to a decrease in the rate of net carbon accumulation in forest carbon stocks and cropland remaining cropland, as well as an increase in emissions from land converted to settlements.

Methane Emissions

Methane (CH_4) is significantly more effective than CO_2 at trapping heat in the atmosphere: by a factor of 28 over a 100-year time frame based on the IPCC *Fifth Assessment Report* estimate (IPCC 2013). Over the last 250 years, the concentration of CH_4 in the atmosphere increased by 161.9 percent (IPCC 2013; NOAA/ESRL 2024b). Within the United States, the main anthropogenic sources of CH_4 include enteric fermentation from domestic livestock, natural gas systems, landfills, domestic livestock manure management, flooded land, coal mining, and petroleum systems (see Figure ES-8).

Figure ES-8: 2022 Sources of CH_4 Emissions



Note: "Other Energy" includes CH_4 emissions from abandoned oil and gas wells, abandoned underground coal mines, incineration of waste, and mobile combustion. "Other Waste" includes CH_4 emissions from anaerobic digestion at biogas facilities and composting. "Other Industrial Processes" includes CH_4 emissions from carbide production and consumption, ferroalloy production, iron and steel production and metallurgical coke production, and petrochemical production. "Other LULUCF" includes the CH_4 reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, coastal wetlands remaining coastal wetlands, and land converted to coastal wetlands.

Overall, CH_4 emissions in the United States in 2022, including LULUCF CH_4 emissions, accounted for 760.8 MMT CO_2 Eq., representing a decrease of 17.7 percent (164.0 MMT CO_2 Eq.) since 1990 and 2.8 percent (21.8 MMT CO_2 Eq.) since 2021. Significant trends for the largest sources of anthropogenic CH_4 emissions include the following:

- Enteric fermentation was the largest anthropogenic source of CH_4 emissions in the United States in 2022, accounting for 27.4 percent of total CH_4 emissions and 3.0 percent of total gross emissions. Emissions have increased by 5.2 percent (9.5 MMT CO_2 Eq.) since 1990. This increase in emissions from 1990 to 2022 generally follows the increasing trends in cattle populations.
- Natural gas systems were the second largest anthropogenic source category of CH_4 emissions in the United States in 2022, accounting for 24.6 percent of total CH_4 emissions and 2.7 percent of total gross emissions. Emissions have decreased by 20.9 percent (45.7 MMT CO_2 Eq.) since 1990, largely due to decreases in emissions from distribution, transmission, and storage.
- Landfills were the third largest anthropogenic source of CH_4 emissions in the United States in 2022, accounting for 17.1 percent of total CH_4 emissions and 1.9 percent of total gross emissions and representing a decrease of 39.4 percent (78.0 MMT CO_2 Eq.) since 1990, with small year-to-year increases. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series.[16]

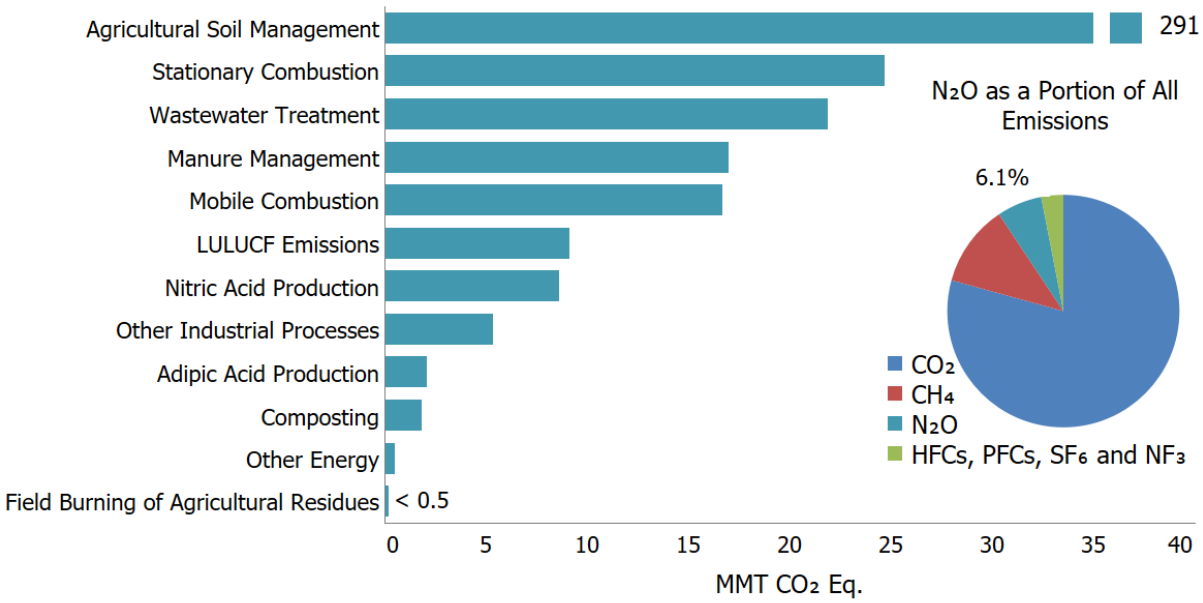
Nitrous Oxide Emissions

Nitrous oxide (N_2O) is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is 265 times more powerful than CO_2 at trapping heat in the atmosphere over a 100-year time frame (IPCC 2013). Since 1750, the global atmospheric concentration of N_2O has

[16] Carbon dioxide emissions from landfills are not included specifically in summing waste sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs and decay of disposed wood products are accounted for in the estimates for LULUCF.

risen by 24.3 percent (IPCC 2013; NOAA/ESRL 2024c). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, wastewater treatment, stationary fuel combustion, manure management, fuel combustion in motor vehicles, and nitric acid production (see Figure ES-9).

Figure ES-9: 2022 Sources of N_2O Emissions



Note: "Other Industrial Processes" includes N_2O emissions from caprolactam, glyoxal, and glyoxylic acid production; the electronics industry; and product uses. "Other Energy" includes N_2O emissions from petroleum systems, natural gas systems, and incineration of waste. LULUCF emissions include N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, coastal wetlands remaining coastal wetlands, forest soils, and settlement soils.

Overall, N_2O emissions in the United States in 2022, including LULUCF N_2O emissions, accounted for 398.8 MMT CO_2 Eq., representing a decrease of 3.4 percent (14.2 MMT CO_2 Eq.) since 1990 and a decrease of 2.5 percent (10.1 MMT CO_2 Eq.) since 2021. Significant trends for the largest sources of anthropogenic N_2O emissions include the following:

- Agricultural soils were the largest anthropogenic source of N_2O emissions in 2022, accounting for 74.6 percent of N_2O emissions and 4.6 percent of total gross greenhouse gas emissions in the United States. These emissions increased by 0.7 percent (2.0 MMT CO_2 Eq.) from 1990 to 2022 but fluctuated during that period due to annual variations in weather patterns, fertilizer use, and crop production.
- Stationary combustion was the second largest source of anthropogenic N_2O emissions in 2022, accounting for 6.3 percent of N_2O emissions and 0.4 percent of total gross U.S. greenhouse gas emissions in 2022. Stationary combustion emissions peaked in 2007 and steadily decreased until 2020. Emissions increased in 2021 and 2022. Stationary combustion emissions have increased by 10.6 percent (2.4 MMT CO_2 Eq.) since 1990.
- Wastewater treatment, both domestic and industrial, was the third largest anthropogenic source of N_2O emissions in 2022, accounting for 5.6 percent of N_2O emissions and 0.3 percent of total gross greenhouse gas emissions in the United States in 2022. Emissions from wastewater treatment increased by 48.2 percent (7.1 MMT CO_2 Eq.) since 1990 as a result of growing U.S. population and protein consumption.

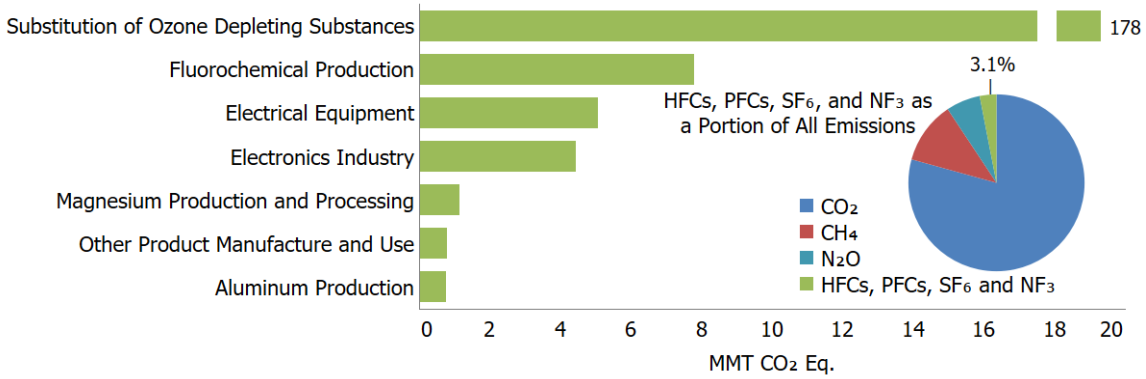
HFC, PFC, SF_6, and NF_3 Emissions

Hydrofluorocarbons (HFCs) are synthetic chemicals that are used as alternatives to ozone depleting substances (ODS), which are being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. Hydrofluorocarbons do not deplete the stratospheric ozone layer and therefore have been used as alternatives under the Montreal Protocol.

Perfluorocarbons (PFCs) are emitted from the production of electronics and aluminum and also (in smaller quantities) from their use as alternatives to ODS. Sulfur hexafluoride (SF_6) is emitted from the manufacturing and use of electrical equipment as well as the production of electronics and magnesium. NF_3 is emitted from electronics production. HFCs are also emitted during production of HCFC-22 and electronics (see Figure ES-10).

HFCs, PFCs, SF_6, and NF_3 are potent greenhouse gases. In addition to having very high GWPs, SF_6, NF_3, and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated (IPCC 2021).

Figure ES-10: 2022 Sources of HFCs, PFCs, SF_6, and NF_3 Emissions



Some significant trends for the largest sources of U.S. HFC, PFC, SF_6, and NF_3 emissions include the following:

- Hydrofluorocarbon and perfluorocarbon emissions resulting from their use as substitutes for ODS (e.g., chlorofluorocarbons [CFCs]) are the largest share of fluorinated emissions (89.9 percent) in 2022 and have been consistently increasing, from small amounts since 1990. This increase over the time series was largely the result of efforts to phase out CFCs and other ODS in the United States.
- Sulfur hexafluoride emissions from electrical equipment decreased by 79.4 percent (19.6 MMT CO_2 Eq.) from 1990 to 2022. There are two factors contributing to this decrease: (1) a sharp increase in the price of SF_6 during the 1990s and (2) a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.
- HFC, PFC, SF_6, and NF_3 emissions from fluorochemical production decreased by 89.0 percent (63.2 MMT CO_2 Eq.) from 1990 to 2022 due to a reduction in the HFC-23 emission rate from HCFC-22 production (kg HFC-23 emitted/kg HCFC-22 produced), the imposition of emissions controls at production facilities, and a decrease in SF_6 production (due to the cessation of production at the major SF_6 production facility in 2010).
- PFC emissions from aluminum production decreased by 96.1 percent (18.5 MMT CO_2 Eq.) from 1990 to 2022, due to both industry emission reduction efforts and lower domestic aluminum production.

ES.3 Overview of Sector Emissions and Trends

Figure ES-11 and Table ES-3 aggregate emissions and sinks by the sectors defined by the UNFCCC and Paris Agreement reporting guidelines and methodological framework in the IPCC guidelines to promote comparability across countries. Over the 33-year period of 1990 to 2022, total emissions from the Energy and Waste sectors decreased by 3.4 percent (181.2 MMT CO_2 Eq.) and 29.3 percent (69.1 MMT CO_2 Eq.) respectively. Emissions from the Industrial Processes and Product Use and Agriculture sectors grew by 3.9 percent (14.4 MMT CO_2 Eq.), and 7.7 percent (42.2 MMT CO_2 Eq.), respectively. Over the same period, the overall net flux from LULUCF (i.e., the net sum of all CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.) decreased by 12.5 percent (122.5 MMT CO_2 Eq.) and resulted in a removal of 854.2 MMT CO_2 Eq. in 2022.

Figure ES-11: U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector

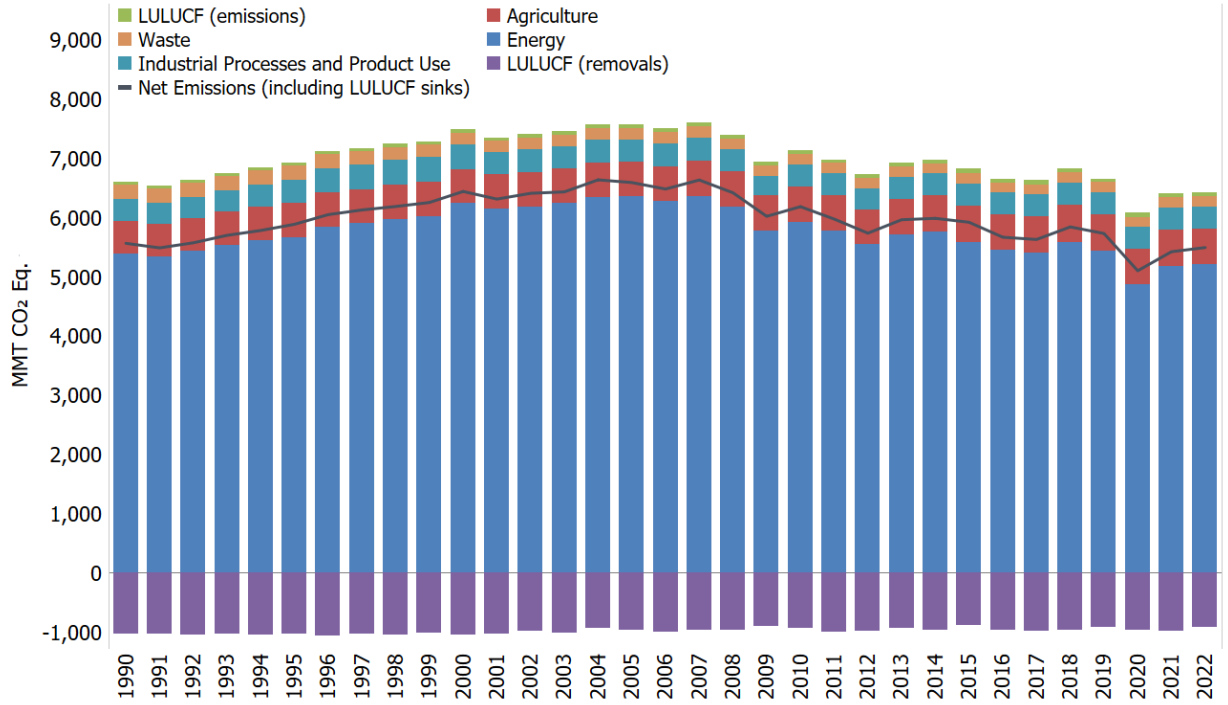


Table ES-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector (MMT CO_2 Eq.)

UNFCCC/IPCC Sector	1990	2000	2018	2019	2020	2021	2022	Percent Change Since 1990
Energy	5,381.0	6,349.5	5,570.0	5,422.4	4,862.6	5,173.3	5,199.8	-3.4%
Industrial Processes and Product Use	368.8	371.3	367.2	371.9	367.9	381.6	383.2	3.9%
Agriculture	551.1	581.8	642.4	620.1	599.7	604.8	593.4	7.7%
Waste	235.9	192.0	173.2	175.8	171.7	169.2	166.9	-29.3%
Total Gross Emissions[a] (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[b]	(976.7)	(907.6)	(915.5)	(863.6)	(904.4)	(910.5)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)[c]	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] Total emissions without LULUCF.

[b] The LULUCF sector net total is the sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

[c] Net emissions with LULUCF.

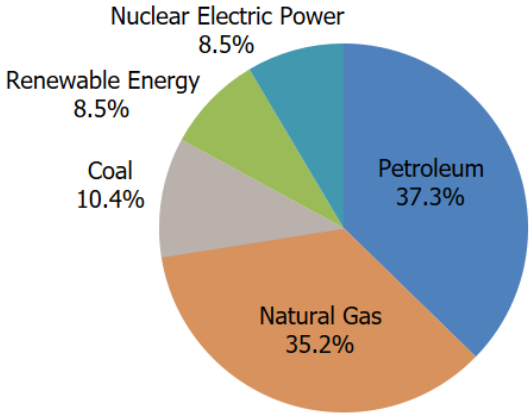
Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and the use of fossil fuels for non-energy purposes. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2022. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.2 percent and 10.8 percent of total U.S. emissions of each gas, respectively).[17] Overall, emission sources in the Energy chapter account for a combined 82.0 percent of total gross U.S. greenhouse gas emissions in 2022. Emissions from energy increased by 0.5 percent (26.5 MMT CO_2 Eq.) since 2021, but they have decreased by 3.4 percent (181.2 MMT CO_2 Eq.) since 1990.

In 2022, 83.0 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 17.0 percent came from other energy sources, such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-12).

Figure ES-12: 2022 U.S. Energy Consumption by Energy Source (Percent)



Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter contains greenhouse gas emissions generated and emitted as the byproducts of non-energy-related industrial processes, which involve the chemical or physical transformation of raw materials and can release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). These processes include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., other uses of carbonates, other uses of soda ash not associated with glass manufacturing, ceramics production, and non-metallurgical magnesia production), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, other fluorochemical production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption. Most of these industries also emit CO_2 from fossil fuel combustion which, in line with UNFCCC/IPCC sectoral definitions, is included in the Energy sector.

[17] The contribution of energy non-CO_2 emissions is based on gross totals and excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related CH_4 and N_2O including LULUCF non-CO_2 emissions is 37.1 percent and 9.8 percent respectively.

This chapter also contains emissions resulting from the release of HFCs, PFCs, SF_6, and NF_3 and other man-made compounds used in industrial manufacturing processes and by end-consumers (e.g., residential and mobile air conditioning). These industries include electronics manufacturing, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by electronics industry and anesthetic and aerosol applications, PFCs and SF_6 are emitted in other product use, and CO_2 is consumed and emitted through various end-use applications. In 2022, emissions resulting from use of the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) by end-consumers was the largest source of IPPU emissions and accounted for 46.5 percent of total IPPU emissions.

IPPU activities are responsible for 3.3, less than 0.5, and 4.1 percent of total U.S. CO_2, CH_4, and N_2O emissions respectively as well as for all U.S. emissions of fluorinated gases including HFCs, PFCs, SF_6 and NF_3. Overall, emission sources in the IPPU chapter accounted for 6.0 percent of U.S. greenhouse gas emissions in 2022. IPPU emissions have increased by 0.4percent (1.6 MMT CO_2 Eq.) since 2021 and by 3.9 percent (14.4 MMT CO_2 Eq.) since 1990, mostly due to increased use of ODS substitutes (e.g., HFCs).

Agriculture

The Agriculture chapter contains information on anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and some agricultural CO_2, CH_4, and N_2O fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry chapter).

Several agricultural activities contribute directly to emissions of greenhouse gases including the following sources: agricultural soil management, enteric fermentation in domestic livestock, livestock manure management, rice cultivation, urea fertilization, liming, and field burning of agricultural residues.

In 2022, agricultural activities were responsible for 9.4 percent of total gross U.S. greenhouse gas emissions. Agriculture sector emissions decreased by 11.4 MMT CO_2 Eq. (1.9 percent) since 2021 and have increased by 42.2 MMT CO_2 Eq. (7.7 percent) since 1990, mostly from trends in enteric fermentation and manure management. Methane, N_2O, and CO_2 are greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented 36.6 percent of total CH_4 emissions from anthropogenic activities in 2022. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to U.S. N_2O emissions in 2022, accounting for 74.6 percent of total N_2O emissions. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities.

Land Use, Land-Use Change, and Forestry

The LULUCF chapter contains emissions and removals of CO_2 and emissions of CH_4 and N_2O from managed lands in the United States. Consistent with the *2006 IPCC Guidelines*, emissions and removals from managed lands are considered to be anthropogenic, while emissions and removals from unmanaged lands are considered to be natural.[18] The share of managed land in the United States is approximately 95 percent of total land included in the Inventory.[19] More information on the definition of managed land used in the *Inventory* is provided in Chapter 6.

Overall, the *Inventory* results show that managed land is a net sink for CO_2 (C sequestration). The primary drivers of fluxes on managed lands include forest management practices, tree planting in urban areas, the management of agricultural soils, lands remaining and lands converted to reservoirs and other constructed waterbodies, landfilling

[18] See http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_01_Ch1_Introduction.pdf.

[19] The current land representation does not include land in U.S. Territories, but there are planned improvements to include these regions in future *Inventories*. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2 in Chapter 6 of this report.

of yard trimmings and food scraps, and activities that cause changes in carbon stocks in coastal wetlands. The main drivers for forest carbon sequestration include forest growth and increasing forest area (i.e., afforestation), as well as a net accumulation of carbon stocks in harvested wood pools. The net sequestration in settlements remaining settlements, which occurs predominantly from urban forests (i.e., settlement trees) and landfilled yard trimmings and food scraps, is a result of net tree growth and increased urban forest area, as well as long-term accumulation of carbon from yard trimmings and food scraps in landfills.

The LULUCF sector in 2022 resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 CO_2 Eq.[20] The removals of carbon offset 14.5 percent of total gross greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 represented 1.2 percent of net greenhouse gas emissions.[21] Carbon dioxide removals from carbon stock changes are presented in Table ES-4 along with CH_4 and N_2O emissions for LULUCF source categories.

Between 1990 and 2022, total carbon sequestration in the LULUCF sector decreased by 10.9 percent, primarily due to a decrease in the rate of net carbon accumulation in forests and in cropland remaining cropland, as well as an increase in CO_2 emissions from land converted to settlements. The overall net flux from LULUCF (i.e., net sum of all CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.) resulted in a removal of 854.2 MMT CO_2 Eq. in 2022.

Flooded lands were the largest source of CH_4 emissions from the LULUCF sector and the fifth largest source overall net CH_4 emissions in 2022. Forest fires were the second largest source of CH_4 emissions, followed by coastal wetlands remaining coastal wetlands. Forest fires were the largest source of N_2O emissions from the LULUCF sector in 2022.

Table ES-4: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Forest Land Remaining Forest Land[a]	(968.8)	(860.1)	(863.4)	(807.0)	(846.3)	(823.9)	(771.7)
Land Converted to Forest Land[b]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland[c]	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland[d]	24.6	24.9	29.7	28.9	17.1	11.5	14.0
Land Converted to Grassland[c]	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands[e]	36.8	39.4	38.2	38.1	38.1	38.1	38.1
Land Converted to Wetlands[e]	7.2	1.8	0.7	0.7	0.7	0.7	0.7
Settlements Remaining Settlements[f]	(109.1)	(115.2)	(131.0)	(131.5)	(131.8)	(132.3)	(132.3)
Land Converted to Settlements[c]	57.2	77.1	71.4	70.2	68.8	68.2	68.2
LULUCF Carbon Stock Change[g]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Emissions[h]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1
LULUCF Sector Net Total[i]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products, emissions from fires on both forest land remaining forest land and land converted to forest land, emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land, and CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[20] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[21] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[b] Includes the net changes to carbon stocks stored in all forest ecosystem pools.
[c] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.
[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.
[e] Estimates include CH_4 emissions from flooded land remaining flooded land and land converted to flooded land.
[f] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.
[g] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land use conversion categories.
[h] LULUCF emissions subtotal includes the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Emissions values are included in land-use category rows.
[i] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Waste

The Waste chapter contains emissions from waste management activities (except the incineration of waste, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic greenhouse gas emissions from waste management activities, accounting for 71.8 percent of total greenhouse gas emissions from waste management activities, and 17.1 percent of total U.S. CH_4 emissions.[22] Additionally, wastewater treatment accounted for 25.6 percent of total Waste sector greenhouse gas emissions, 3.0 percent of U.S. CH_4 emissions, and 5.6 percent of U.S. N_2O emissions in 2022. Emissions of CH_4 and N_2O from commercial composting are also included in this chapter, accounting for 1.5 percent (2.6 MMT CO_2 Eq.) and 1.1 percent (1.8 MMT CO_2 Eq.) of overall waste sector emissions, respectively. Anaerobic digestion at biogas facilities generated CH_4 emissions, accounting for less than 0.05 percent of emissions from the Waste sector. Overall, emission sources in the Waste chapter accounted for 2.6 percent of total gross U.S. greenhouse gas emissions in 2022. Waste sector emissions decreased by 1.4 percent (2.3 MMT CO_2 Eq.) since 2021 and by 29.3 percent (69.1 MMT CO_2 Eq.) since 1990.

ES.4 Other Information

Emissions and Sinks by Economic Sector

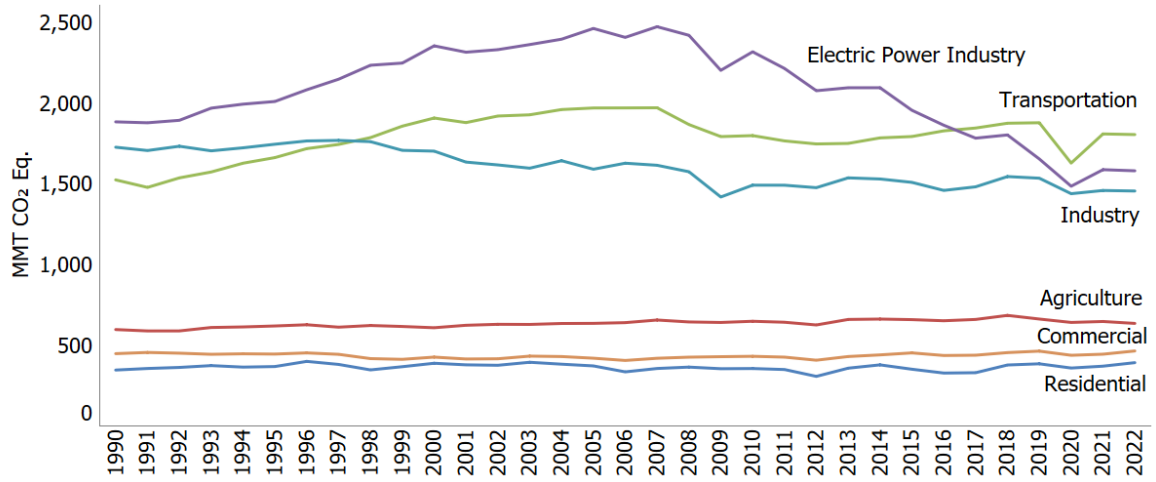
In addition to the Paris Agreement and UNFCCC sectors and methods defined by the IPCC, this report also characterizes emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture.[23] Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. For more information on trends in the Land Use, Land-Use Change, and Forestry sector, see Section ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks.

[22] Landfills also store carbon, due to incomplete degradation of organic materials such as harvest wood products, yard trimmings, and food scraps, as described in the Land Use, Land-Use Change, and Forestry chapter of the Inventory report. Also, the estimated total methane emissions used to estimate contribution excludes methane emissions from the LULUCF sector.

[23] The agriculture economic sector includes emissions from fossil fuel combustion and electricity use within the agricultural sector.

Figure ES-13 shows the trend in emissions by economic sector from 1990 to 2022, and Table ES-5 summarizes emissions from each of these economic sectors.

Figure ES-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table ES-5: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

Economic Sectors	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Transportation	1,521.4	1,965.9	1,871.6	1,874.6	1,625.3	1,805.5	1,801.5	18.4%
Electric Power Industry	1,880.2	2,457.4	1,799.2	1,650.8	1,482.2	1,584.4	1,577.5	-16.1%
Industry	1,723.3	1,587.3	1,541.9	1,531.8	1,435.9	1,455.8	1,452.5	-15.7%
Agriculture	595.9	634.3	683.5	661.0	640.0	645.9	634.0	6.4%
Commercial	447.0	418.9	453.5	462.6	436.9	443.7	463.7	3.7%
Residential	345.6	371.2	376.8	384.2	358.0	369.6	391.3	13.2%
U.S. Territories	23.4	59.7	26.3	25.1	23.4	23.9	22.7	-3.1%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[a]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) emissions are presented without LULUCF. Total net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Using this categorization, emissions from transportation activities accounted for the largest portion (28.4 percent) of total gross U.S. greenhouse gas emissions in 2022. Electric power accounted for the second largest portion (24.9 percent) of U.S. greenhouse gas emissions in 2022, while emissions from industry accounted for the third largest portion (22.9 percent). Emissions from industry have in general declined over the past decade, due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and energy efficiency improvements.

The remaining 23.8 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.0 percent of U.S. emissions; unlike other economic sectors, agricultural sector

emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation. An increasing amount of carbon is stored in agricultural soils each year, but this CO_2 sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for 7.3 percent and 6.2 percent of emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in carbon stocks in coastal wetlands.

Electricity is ultimately used in the economic sectors described above. Table ES-6 presents greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power generation are allocated to the economic sectors in which the electricity is used). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electric power were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity for each end-use sector (EIA 2024).[24] These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from incineration of waste, CH_4 and N_2O from stationary sources, and SF_6 from electrical equipment systems.

When emissions from electricity use are distributed among these end-use sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (29.5 percent and 28.5 percent, respectively) in 2022. The commercial and residential sectors contributed the next largest shares of total gross U.S. greenhouse gas emissions in 2022 (15.8and 15.3 percent, respectively). Emissions from the commercial and residential sectors increase substantially when emissions from electricity use are included, due to their relatively large share of electricity use for energy (e.g., lighting, cooling, appliances). Figure ES-14 shows the trends in these emissions by sector from 1990 to 2022.

Table ES-6: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed by Economic Sector (MMT CO_2 Eq.)

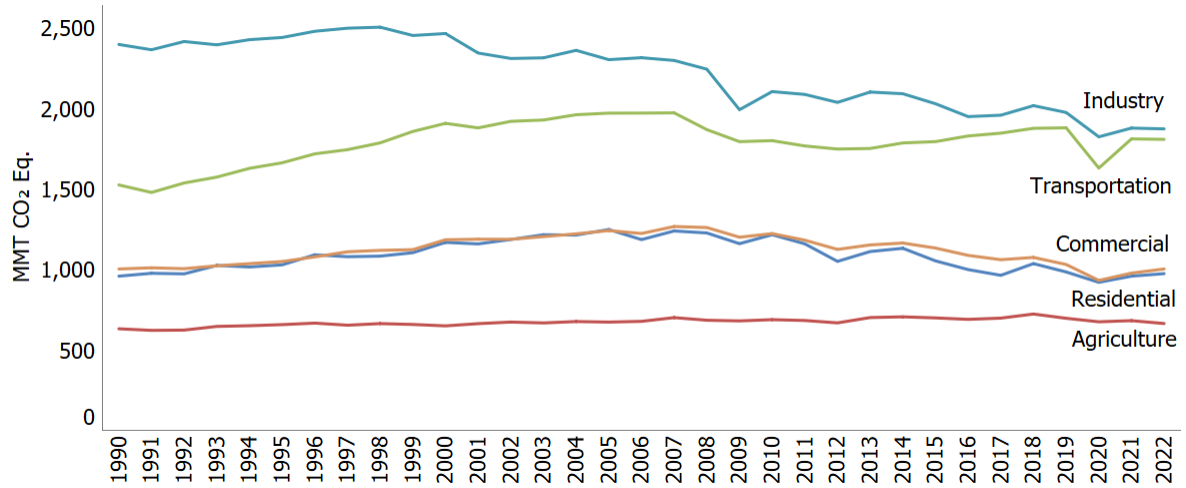
Economic Sectors	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Industry	2,397.3	2,302.9	2,017.1	1,974.8	1,823.5	1,877.8	1,872.9	-21.9%
Transportation	1,524.6	1,970.8	1,876.5	1,879.5	1,629.5	1,810.6	1,807.8	18.6%
Commercial	1,002.5	1,241.1	1,074.3	1,030.5	931.5	976.8	1,002.6	0.0%
Residential	958.0	1,247.7	1,035.9	984.0	919.5	958.0	973.5	1.6%
Agriculture	631.1	672.6	722.7	696.3	674.4	681.6	663.6	5.2%
U.S. Territories	23.4	59.7	26.3	25.1	23.4	23.9	22.7	-3.1%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**-3.0%**
LULUCF Sector Net Total[a]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	-12.5%
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**-1.3%**

[a] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

[24] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to Territories data.

Figure ES-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Box ES-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total (gross) greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) aggregate energy use, because energy-related activities are the largest sources of emissions; (2) energy use per capita as a measure of efficiency; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

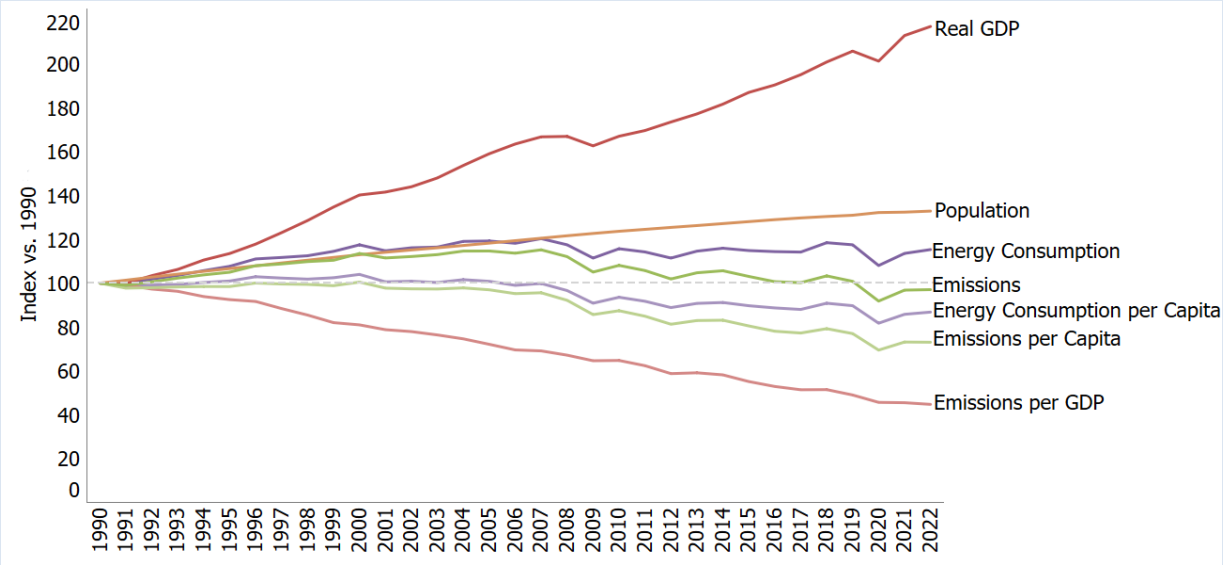
Table ES-7 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have declined at an average annual rate of 0.01 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use and fossil fuel consumption, and overall gross domestic product (GDP), and national population (see Figure ES-15). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use, and fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.9 percent since 2005. Since 2005, GDP and national population, generally, continued to increase while energy has decreased slightly—noting 2020 was impacted by the COVID-19 pandemic.

Table ES-7: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2018	2019	2020	2021	2022	Avg. Annual Growth Rate Since 1990[a]	Avg. Annual Growth Rate Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	101	92	97	97	-0.1%	-0.9%
Energy Use[c]	100	119	118	117	107	113	115	0.5%	-0.2%
GDP[d]	100	159	201	206	201	213	217	2.5%	1.9%
Population[e]	100	118	130	131	132	132	133	0.9%	0.7%

+ Absolute value does not exceed 0.05 percent.
[a] Average annual growth rate.
[b] Gross total GWP-weighted values.
[c] Energy content-weighted values (EIA 2024).
[d] GDP in chained 2017 dollars (BEA 2024).
[e] U.S. Census Bureau (2024).

Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP)



Source: BEA (2024), U.S. Census Bureau (2024), and emission estimates in this report.

Key Categories

The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) defines key categories as "inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or

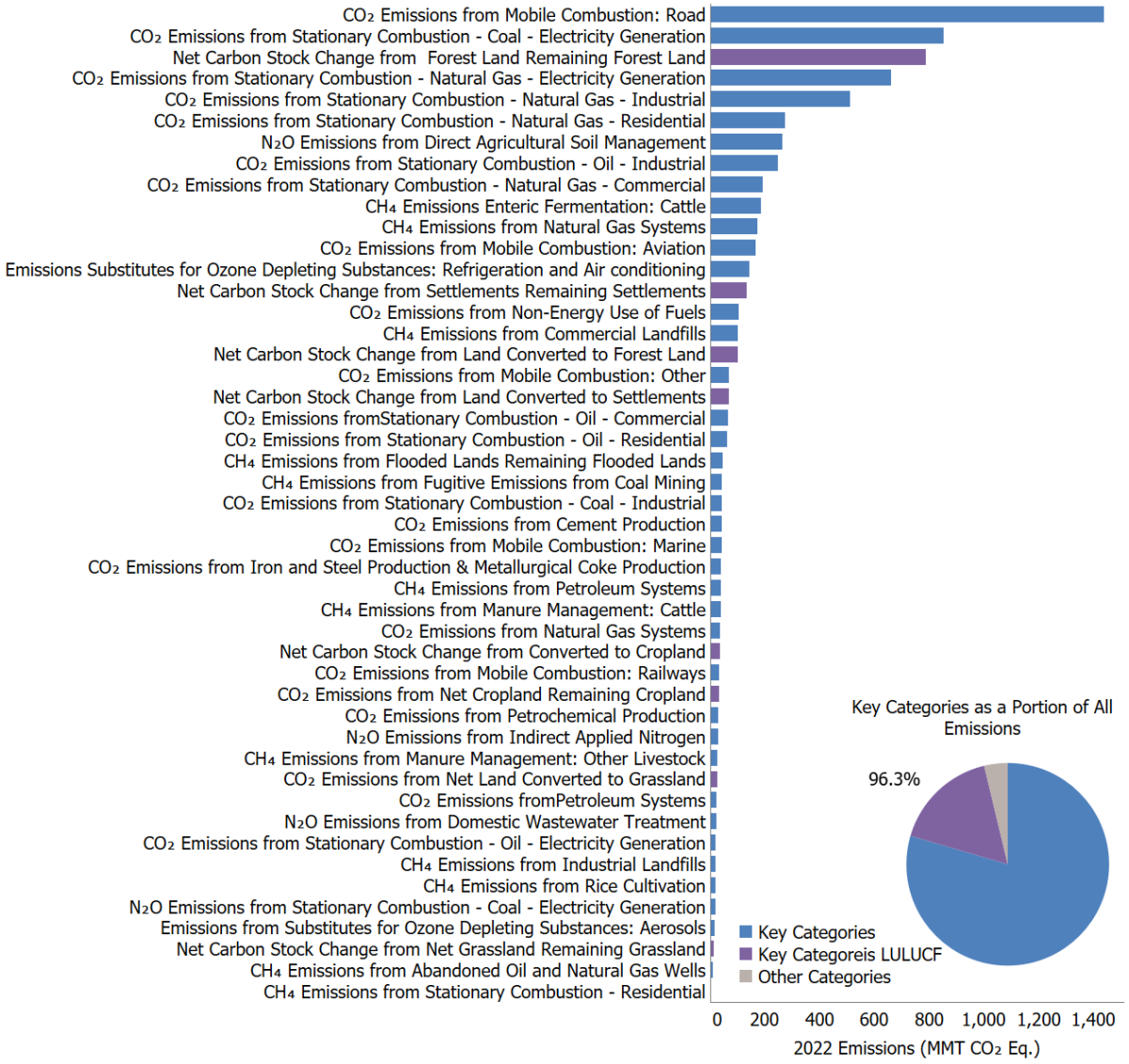
the level of uncertainty in emissions or removals."[25] A key category analysis identifies priority source or sink categories for focusing efforts to improve overall Inventory quality. In addition, a qualitative review of key categories and non-key categories can also help identify additional source and sink categories to consider for improvement efforts, including reducing uncertainty.

Figure ES-16 presents the 2022 key categories identified by the Approach 1 level assessment, including the LULUCF sector. A level assessment using Approach 1 identifies all source and sink categories that cumulatively account for 95 percent of total (i.e., gross) emissions in a given year when assessed in descending order of absolute magnitude.

For a complete list of key categories and more information regarding the overall key category analysis, including approaches accounting for uncertainty and the influence of trends of individual source and sink categories, see the Introduction chapter, Section 1.5, and Annex 1.

[25] See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006) and IPCC (2019). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html and https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch04_MethodChoice.pdf.

Figure ES-16: 2022 Key Categories (Approach 1 including LULUCF)[a]



Note: For a complete list of key categories and detailed discussion of the underlying key category analysis, see Annex 1. Bars indicate key categories identified using Approach 1 level assessment including the LULUCF sector. The absolute values of net CO_2 emissions from LULUCF are presented in this figure but reported separately from gross emissions totals. Refer to Table ES-4 for a breakout of emissions and removals for LULUCF by source/sink category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks continuous improvements to the quality, transparency, and usability of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. To assist in these efforts, the United States implemented a systematic approach to QA/QC. The procedures followed for the Inventory have been formalized in accordance with the U.S. Inventory QA/QC plan, and the UNFCCC reporting guidelines and *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The QA process includes expert and public reviews for the Inventory estimates and this report.

Box ES-3: Use of Ambient Measurements Systems for Validation of Emission Inventories

In following Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC, as well as relevant decisions under those agreements to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally accepted methods in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines) and, where appropriate, its supplements and refinements.[26] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[27] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the Inventory in a manner consistent with this *Inventory* report's transparency of its calculation methodologies, and the ability of inverse modeling techniques to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that emission estimates derived from atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6). Further, it identified fluorinated gases as particularly suitable for such comparisons due their limited natural sources, their generally long atmospheric lifetimes, and well-understood loss mechanisms, which makes it relatively more straightforward to model their emission fluxes from observed mass quantities. Unlike emissions of CO_2, CH_4, and N_2O, emissions of fluorinated greenhouse gases are almost exclusively anthropogenic, meaning that the fluorinated greenhouse gas emission sources included in this Inventory account for the majority of the total U.S. emissions of these gases detectable in the atmosphere. This evaluation approach is also useful for gases and sources with larger uncertainties in available bottom-up inventory methods and data, such as emissions of CH_4, which are primarily from uncertain biological (e.g., enteric fermentation) and fugitive (e.g., natural gas production) activities.

In this *Inventory*, EPA includes the results from current and previous comparisons between fluorinated gas emissions inferred from atmospheric measurements and fluorinated gas emissions estimated based on bottom-up measurements and modeling. These comparisons, performed for HFCs and SF_6 respectively, are described under the QA/QC and Verification discussions in Chapter 4, Sections 4.25 Substitution of Ozone Depleting Substances and 4.26 Electrical Equipment, in the IPPU chapter of this report.

Consistent with the *2019 Refinement*, a key element to facilitate such comparisons is a spatially-explicit (or gridded inventory as an input to inverse modeling. To improve the ability to compare methane emissions from the national-level greenhouse gas inventory with observation-based estimates , a team of researchers from U.S. EPA, SRON Netherlands Institute for Space Research, Harvard University, and Lawrence Berkely National Laboratory and other coauthors developed a time series of anthropogenic methane emissions maps with 0.1° x 0.1° (10 km x 10 km) spatial resolution and monthly temporal resolution for the contiguous United States.[28] The gridded methane inventory is designed to be consistent with the U.S. EPA *Inventory of U.S. Greenhouse Gas*

[26] See http://www.ipcc-nggip.iges.or.jp/public/index.html.

[27] See http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf.

[28] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Emissions and Sinks estimates, which presents national totals for different source types.[29] The development of this gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to the use of atmospheric concentration measurement data for comparison with Inventory data, information from top-down studies is directly incorporated in the natural gas systems calculations to quantify emissions from certain well blowout events.

Uncertainty Analysis of Emission and Sink Estimates

Uncertainty assessment is an essential element of a complete inventory of greenhouse gas emissions and removals because it helps to inform and prioritize inventory improvements. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), Volume 1, Chapter 3 and require that countries provide single estimates of uncertainty for source and sink categories. In addition to quantitative uncertainty assessments, a qualitative discussion of uncertainty is presented for each source and sink category identifying specific factors affecting the uncertainty surrounding the estimates provided in accordance with UNFCCC reporting guidelines. Some of the current estimates, such as those for CO_2 emissions from energy-related combustion activities, are considered to have low uncertainties. This is because the amount of CO_2 emitted from energy-related combustion activities is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel, and for the United States, the uncertainties associated with estimating those factors are relatively small. For some other categories of emissions and sinks, however, inherent variability or a lack of data increases the uncertainty or systematic error associated with the estimates presented. Finally, an analysis is conducted to assess uncertainties associated with the overall emissions, sinks, and trends estimates. The overall uncertainty surrounding total net greenhouse gas emissions is estimated to be -6 to +6 percent in 1990 and -5 to +6 percent in 2022. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -3 to +4 percent in 1990 and -2 to +4 percent in 2022.

[29] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

1. Introduction

This report presents an inventory of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 2022 compiled by the United States government. A summary of source and sink category estimates is provided in Table 2-1, Table 2-2, andTable 2-4 by gas and IPCC sector in the Trends in Greenhouse Gas Emissions and Sinks chapter. The emission and sink estimates in these tables are presented throughout the main report in both CO_2 equivalents (CO_2 Eq.[30] and unweighted units). This report also discusses the methods and data used to calculate the emission and sink estimates.

The United States is party to both the 1992 UNFCCC and the 2015 Paris Agreement. The Paris Agreement set a global temperature goal–holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C–that articulates with greater precision States' views on what is necessary to meet the UNFCCC's objective of "stabiliz[ing] … greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[31]

The United States is committed to submitting a national inventory of anthropogenic emissions sources and removals by sinks of greenhouse gases by April 15 of each year. The United States has prepared this report, in conjunction with Common Reporting Tables (CRTs) that accompany this report, consistent with its obligations under those agreements.

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation (IPCC 2021). The Paris Agreement and the UNFCCC require use of methods from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and encourages Parties to use the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* and *the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The recently released *2019 Refinement* clarify and elaborate on the existing guidance in the *2006 IPCC Guidelines*, along with providing updates to default values of emission factors and other parameters based on updated science. This report applies both the *2013 Supplement* and updated guidance in the *2019 Refinement* to improve accuracy and completeness of the *Inventory*. For more information on specific uses, see Section 1.4 of this chapter on Methodology and Data Sources.

[30] More information is provided in the Global Warming Potentials section of this chapter on the use of IPCC *Fifth Assessment Report* (AR5) GWP values.

[31] See Paris Agreement, Article 2.1(a); UNFCCC, Article 2.

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC, as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and, where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in this *Inventory* does not preclude alternative examinations (e.g., economic sectors). Rather, this *Inventory* presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP), which is complementary to the U.S. *Inventory*.[32] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[33] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories[34] subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for the 2011 reporting year. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines*. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and removals (e.g., the GHGRP excludes emissions from the Agriculture and Land Use, Land-Use Change, and Forestry sectors), it is an important input to the calculations of national-level emissions in this *Inventory*.

Data presented in this *Inventory* report and EPA's GHGRP are complementary. The GHGRP dataset continues to be an important resource for the *Inventory*, providing not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines* (e.g., higher tier methods). GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in several categories to improve the national estimates presented in this *Inventory*, consistent with IPCC methodological guidance. See Annex 9 for more information on specific uses of GHGRP data in the *Inventory* (e.g., natural gas systems).

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal, oil, and natural gas, along with deforestation, land-use changes, and other activities have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (IPCC 2021). These gases in the atmosphere absorb some of the energy

being radiated from the surface of the Earth that would otherwise be lost to space, essentially acting like a blanket that makes the Earth's surface warmer than it would be otherwise.

Greenhouse gases are necessary to life as we know it. Without greenhouse gases to create the natural heat-trapping properties of the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (USGCRP 2017). Carbon dioxide is also necessary for plant growth. With emissions from biological and geological sources, there is a natural level of greenhouse gases that is maintained in the atmosphere. Human emissions of greenhouse gases and subsequent changes in atmospheric concentrations alter the balance of energy transfers between space and the earth system (IPCC 2021). A gauge of these changes is called radiative forcing, which is a measure of a substance's total net effect on the global energy balance for which a positive number represents a warming effect, and a negative number represents a cooling effect (IPCC 2021). IPCC concluded in its most recent scientific assessment report that it is "unequivocal that human influence has warmed the atmosphere, ocean and land" (IPCC 2021).

As concentrations of greenhouse gases continue to increase from man-made sources, the Earth's temperature is climbing above past levels. The Earth's average land and ocean surface temperature has increased by about 2.0 degrees Fahrenheit from the 1850 to 1900 period to the decade of 2011 to 2020 (IPCC 2021). The last four decades have each been the warmest decade successively at the Earth's surface since at least 1850 (IPCC 2021). Other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level. If greenhouse gas concentrations continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase between 0.27 to 9.99 degrees Fahrenheit (0.15 to 5.55 degrees Celsius) relative to 1995 to 2014 levels by the end of this century, depending on the emissions scenario and the responsiveness of the climate system (IPCC 2021).

For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC,[35] the U.S. Global Change Research Program (USGCRP),[36] and the National Academies of Sciences, Engineering, and Medicine (NAS).[37]

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2021).

Naturally occurring greenhouse gases include water vapor, CO_2, CH_4, N_2O, and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in

---

[32] On October 30, 2009, EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[33] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

[34] See https://www.ccdsupport.com/confluence/pages/viewpage.action?pageId=322699300

[35] See https://www.ipcc.ch/report/ar6/wg1/.

[36] See https://nca2018.globalchange.gov/.

[37] See https://www.nationalacademies.org/topics/climate.

national greenhouse gas inventories.[38] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several other substances that influence the global radiation budget but are short-lived and therefore not well-mixed, leading to spatially variable radiative forcing effects. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (VOCs), CH_4, and nitrogen oxides (NO_x), in the presence of ultraviolet light (sunlight).

Aerosols are extremely small particles or liquid droplets suspended in the Earth's atmosphere that are often composed of sulfur compounds, carbonaceous combustion products (e.g., black carbon), crustal materials (e.g., dust) and other human-induced pollutants. They can affect the absorptive characteristics of the atmosphere (e.g., scattering incoming sunlight away from the Earth's surface, or, in the case of black carbon, absorbing sunlight) and can play a role in affecting cloud formation and lifetime, as well as the radiative forcing of clouds and precipitation patterns.

CO_2, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities (such as fossil fuel combustion, cement production, land-use, land-use change, and forestry, agriculture, or waste management), however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.730 ppm	0.270 ppm	0.01 ppt	34.1 ppt
Atmospheric concentration	419 ppm[a]	1.912 ppm[b]	0.336 ppm[c]	11.02 ppt[d]	85.5 ppt[e]
Rate of concentration change	2.28 ppm/yr[f]	8.83 ppb/yr[f,g]	1.01 ppb/yr[f]	0.32 ppt/yr[f]	0.81 ppt/yr[f]
Atmospheric lifetime (years)	See footnote[h]	11.8	109[i]	About 1,000[j]	50,000

[a] The atmospheric CO_2 concentration is the 2022 annual average at the Mauna Loa, HI station (NOAA/ESRL 2024a). The global atmospheric CO_2 concentration, computed using an average of sampling sites across the world, was 417 ppm in 2022.

[b] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024b).

[c] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024c).

[d] The values presented are global 2022 annual average mole fractions (NOAA/ESRL 2024d).

[e] The 2019 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2021).

[f] The rate of concentration change for CO_2 is an average of the rates from 2007 through 2022 and has fluctuated between 1.5 to 3.0 ppm per year over this period (NOAA/ESRL 2024a). The rate of concentration change for CH_4, N_2O, and SF_6, is the average rate of change between 2007 and 2022 (NOAA/ESRL 2024b; NOAA/ESRL 2024c; NOAA/ESRL 2024d). The rate of concentration change for CF_4 is the average rate of change between 2011 and 2019 (IPCC 2021).

[g] The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 13.22 ppb/year (NOAA/ESRL 2024b).

[38] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

[h] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[i] This table reports the "perturbation lifetime" for both CH_4 and N_2O, which takes into account the interactions between emissions of the gas and its own atmospheric residence time.

[j] The lifetime for SF_6 was revised from 3,200 years to about 1,000 years based on recent studies (IPCC 2021).

Source: Pre-industrial atmospheric concentrations and atmospheric lifetimes for CH_4, and N_2O, are from IPCC (2021), pre-industrial atmospheric concentration for SF_6, is from Rigby (2010), and pre-industrial atmospheric concentration for CF_4 is from Meinhausen (2017).

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of global warming potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Water vapor is the largest contributor to the natural greenhouse effect. Water vapor is fundamentally different from other greenhouse gases in that it can condense and rain out when it reaches high concentrations, and the total amount of water vapor in the atmosphere is in part a function of the Earth's temperature. While some human activities such as evaporation from irrigated crops or power plant cooling release water vapor into the air, these activities have been determined to have a negligible effect on global climate (IPCC 2021). The lifetime of water vapor in the troposphere is on the order of 10 days. Water vapor can also contribute to cloud formation, and clouds can have both warming and cooling effects by either trapping or reflecting heat. Because of the relationship between water vapor levels and temperature, water vapor and clouds serve as a feedback to climate change, such that for any given change in other greenhouse gas concentrations, the total temperature change is greater than would happen in the absence of water vapor. Aircraft emissions can create contrails, which may also develop into contrail-induced cirrus clouds, with complex regional and temporal net radiative forcing effects that currently have a low level of scientific certainty (IPCC 2021).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 419 ppmv in 2022, a 50 percent increase (IPCC 2021; NOAA/ESRL 2024a).[39, 40] The IPCC states that "Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities" (IPCC 2021). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2. In its *Sixth Assessment Report*, the IPCC determined that of the 2.0 degrees of observed warming, the best estimate is that 1.9 degrees of that are due to human influence, with elevated CO_2 concentrations being the most important contributor to that warming (IPCC 2021).

Methane (CH_4). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes and treatment of wastewater. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a byproduct of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 162 percent since 1750, from a pre-industrial value of about 730 ppb to 1,912 ppb in 2022[41] although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to

[39] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2021).

[40] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750 to 1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2021).

[41] This value is the global 2022 annual average mole fraction (NOAA/ESRL 2024b).

about 8.83 ppb/year. The IPCC has estimated that about half of the current CH_4 flux to the atmosphere (and the entirety of the increase in concentration) is anthropogenic, from human activities such as agriculture, fossil fuel production and use, and waste disposal (IPCC 2021).

Methane is primarily removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, creating a feedback that increases the atmospheric lifetime of CH_4 (IPCC 2021). Methane's reactions in the atmosphere also lead to production of tropospheric ozone and stratospheric water vapor, both of which also contribute to climate change. Tropospheric ozone also has negative effects on human health and plant productivity.

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has increased by 24 percent since 1750, from a pre-industrial value of about 270 ppb to 336 ppb in 2022,[42] a concentration that has not been exceeded during at least the last 800 thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2021).

Ozone (O_3). Ozone is present in both the upper stratosphere,[43] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[44] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as CFCs, have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 2021). The depletion of stratospheric ozone and its radiative forcing remained relatively unchanged since 2000 for the last two decades and is starting to decline; recovery is expected to occur shortly after the middle of the twenty-first century (WMO/UNEP 2018).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds and CH_4 mixing with NO_x in the presence of sunlight. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable (IPCC 2021).

Halocarbons, Sulfur Hexafluoride (SF_6), and Nitrogen Trifluoride (NF_3). Halocarbons are, for the most part, man-made chemicals that have direct radiative forcing effects and could also have an indirect effect. Halocarbons that contain chlorine (CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (halons, methyl bromide, and hydrobromofluorocarbons) result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although most CFCs and HCFCs are potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is a greenhouse gas but which also shields the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap

[42] This value is the global 2022 annual average (NOAA/ESRL 2024c).

[43] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[44] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

was placed on the production and importation of HCFCs by non-Article 5 countries, including the United States,[45] beginning in 1996, and then followed by intermediate requirements and a complete phase-out by the year 2030. While ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC, they are reported in this Inventory under Annex 6.2 for informational purposes.

HFCs, PFCs, SF_6, and NF_3 are not ozone depleting substances. The most common HFCs are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but are also emitted as a byproduct of the HCFC-22 (chlorodifluoromethane) manufacturing process. Other contributing sources to HFC emissions include the electronics industry and magnesium production and processing. Currently, these emissions have a small aggregate radiative forcing impact, but it was anticipated that without further controls their contribution to overall radiative forcing would increase, the ERF (effective radiative forcing) of halogenated gases increased by 3.5 percent between 2011 and 2019 primarily due to a decrease in atmospheric mixing-ratios of CFCs and an increase in their replacements (IPCC 2021). On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and which gives EPA authority to phase down HFC production and consumption (i.e., production plus import, minus export), through an allowance allocation program, promulgate certain regulations for purposes of maximizing reclamation and minimizing releases of HFCs and their substitutes from equipment, and facilitate the transition to next-generation technologies through sector-based restrictions, which will lead to lower HFC emissions over time. On October 31, 2022, the United States also ratified the Kigali Amendment to the Montreal Protocol, committing to continued phase down of HFCs. Perfluorocarbons, SF_6, and NF_3 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, SF_6, and NF_3 is also small, but they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2021).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect. Warming effects can occur due to reactions leading to the formation of ozone in the troposphere, but cooling effects can occur due to the role of NO_x as a precursor to nitrate particles (i.e., aerosols) and due to destruction of stratospheric ozone when emitted from very high-altitude aircraft.[46] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2021). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Non-methane Volatile Organic Compounds (NMVOCs). Non-methane volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

[45] Article 5 of the Montreal Protocol covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

[46] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere that are either directly emitted into or are created through chemical reactions in the Earth's atmosphere. Aerosols or their chemical precursors can be emitted by natural events such as dust storms, biogenic or volcanic activity, or by anthropogenic processes such as transportation, coal combustion, cement manufacturing, waste incineration, or biomass burning. Various categories of aerosols exist from both natural and anthropogenic sources, such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, volcanic aerosols, industrial dust, and carbonaceous[47] aerosols (e.g., black carbon, organic carbon). Aerosols can be removed from the atmosphere relatively rapidly by precipitation or through more complex processes under dry conditions.

Aerosols affect radiative forcing differently than greenhouse gases. Their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation (and to a lesser extent scattering, absorption, and emission of terrestrial radiation); and indirectly by increasing cloud droplets and ice crystals that modify the formation, precipitation efficiency, and radiative properties of clouds (IPCC 2021). Despite advances in understanding of cloud-aerosol interactions, the contribution of aerosols to radiative forcing are difficult to quantify because aerosols generally have short atmospheric lifetimes, and have number concentrations, size distributions, and compositions that vary regionally, spatially, and temporally (IPCC 2021).

The net effect of aerosols on the Earth's radiative forcing is believed to be negative (i.e., net cooling effect on the climate). In fact, aerosols contributed a cooling influence of up to 1.4 degrees, offsetting a substantial portion of greenhouse gas warming (IPCC 2021). Because aerosols remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[48] Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a positive radiative forcing by heating the Earth's atmosphere and causing surface warming when deposited on ice and snow (IPCC 2021). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

Global Warming Potentials

A GWP is a quantified measure of the relative globally averaged radiative forcing impacts of emissions of a particular greenhouse gas over time (see Table 1-2). It is defined as the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram (kg) of the gas, relative to that of the reference gas CO_2 (IPCC 2021). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in CO_2 equivalent (CO_2 Eq.).[49] For example, the relationship between a kg of emissions of a gas and a kg of CO_2 Eq. emissions can be expressed as follows and also adapted to other units (e.g. metric tons, etc.):

[47] Carbonaceous aerosols are aerosols that are comprised mainly of carbon and hydrogen. Those carbonaceous aerosols with more hydrogen are classified as "organic carbon", and are generally reflective, while the aerosols that are nearly pure carbon are classified as "black carbon" (also referred to as "soot") and can absorb light (IPCC 2021).

[48] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer lasting negative forcing effect (i.e., a few years) (IPCC 2021).

[49] Carbon comprises 12/44^{ths} of carbon dioxide by weight.

Equation 1-1: Calculating CO_2 Equivalent Emissions

$$\text{kg } CO_2 \text{ Eq.} = (\text{kg emission of gas}) \times (\text{GWP})$$

where,

kg CO_2 Eq.	= kilograms of CO_2 equivalent
kt	= kilograms (equivalent to a thousand metric grams)
GWP	= Global warming potential

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±40 percent.

All estimates are provided throughout the report in both MMT CO_2 equivalents and unweighted units. Recent decisions under the UNFCCC require Parties to use 100-year GWP values from the IPCC *Fifth Assessment Report* (AR5) for calculating CO_2-equivalent emissions in their national reporting by the end of 2024.

> *…Decides that, until it adopts a further decision on the matter, the global warming potential values used by Parties in their reporting under the Convention to calculate the carbon dioxide equivalence of anthropogenic greenhouse gas emissions by sources and removals by sinks shall be based on the effects of greenhouse gases over a 100-year time horizon as listed in table 8.A.1 in appendix 8.A to the contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,[50] excluding the value for fossil methane.*[51]

This reflects updated science and ensures that national greenhouse gas inventories reported by all nations are comparable. In preparation for upcoming UNFCCC requirement,[52] this report reflects CO_2-equivalent greenhouse gas totals using 100-year AR5 GWP values. A comparison of emission values with the previously used 100-year GWP values from IPCC *Fourth Assessment Report* (AR4) (IPCC 2007), and the IPCC *Sixth Assessment Report* (AR6) (IPCC 2021) values can be found in Annex 6.1 of this report. The 100-year GWP values used in this report are listed below in Table 1-2.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. Parties to the UNFCCC have not agreed upon GWP values for these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in this Report

Gas	Atmospheric Lifetime	GWP[a]
CO_2	See footnote[b]	1
CH_4[c]	12.4	28
N_2O	121	265

[50] Intergovernmental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change. TF Stocker, D Qin, G-K Plattner, et al. (eds.). Cambridge and New York: Cambridge University Press. Available at http://www.ipcc.ch/report/ar5/wg1.

[51] See paragraphs 1 and 2 of the decision on common metrics adopted at the 27th UNFCCC Conference of Parties (COP27), available online at https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

[52] See Annex to decision 18/CMA.1, available online at https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf The Paris Agreement reporting guidelines also clarified use of the 100-year GWPs listed in table 8.A.1 in Annex 8.A of Chapter 8 of the *Fifth Assessment Report* (AR5) of the Intergovernmental Panel on Climate Change, excluding the value for fossil methane. United Nations Framework Convention on Climate Change, see paragraph 25 of Decision 5/CMA.3 available online at https://unfccc.int/sites/default/files/resource/CMA2021_L10a2E.pdf.

HFC-23	222	12,400
HFC-32	5.2	677
HFC-41[d]	2.8	116
HFC-125	28.2	3,170
HFC-134a	13.4	1,300
HFC-143a	47.1	4,800
HFC-152a	1.5	138
HFC-227ea	38.9	3,350
HFC-236fa	242	8,060
CF_4	50,000	6,630
C_2F_6	10,000	11,100
C_3F_8	2,600	8,900
c-C_4F_8	3,200	9,540
SF_6	3,200	23,500
NF_3	500	16,100
Other Fluorinated Gases		See Annex 6

[a] 100-year time horizon.
[b] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.
[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.
[d] See Table A-1 of 40 CFR Part 98
Source: IPCC (2013).

Box 1-2: The IPCC Sixth Assessment Report and Global Warming Potentials

In 2021, the IPCC published its *Sixth Assessment Report* (AR6), which updated its comprehensive scientific assessment of climate change. Within the AR6 report, the GWP values of gases were revised relative to previous IPCC assessment reports, e.g., the IPCC *Fifth Assessment Report* (AR5) (IPCC 2014). Although the AR5 GWP values are used throughout this report, consistent with UNFCCC reporting requirements, it is straight-forward to review the changes to the GWP values and their impact on estimates of the total GWP-weighted emissions of the United States. In the AR6, the IPCC used more recent estimates of the atmospheric lifetimes and radiative efficiencies of some gases and updated background concentrations. The AR6 now includes climate-carbon feedback effects for non-CO_2 gases, improving the consistency between treatment of CO_2 and non-CO_2 gases. Indirect effects of gases on other atmospheric constituents (such as the effect of methane on ozone) have also been updated to match more recent science.

Table 1-3 presents the new GWP values, relative to those presented in the AR5, using the 100-year time horizon common to Paris Agreement and UNFCCC reporting.[53] Updated reporting guidelines under the Paris Agreement require the United States and other countries to shift to use of the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013) 100-year GWP values (without feedbacks) for national inventory reporting.[54] All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use 100-year GWPs from other recent IPCC Assessment Reports are presented in detail in Annex 6.1 of this report.

[53] See Decision 7/CP.27 included in https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf.

[54] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement.

Table 1-3: Comparison of 100-Year GWP values

100-Year GWP Values				Comparisons to AR5	
Gas	AR5[a]	AR5 with feedbacks[b]	AR6[c]	AR5 with feedbacks[b]	AR6[c]
CO_2	1	1	1	NC	NC
CH_4[d]	28	34	27	6	(1)
N_2O	265	298	273	33	8
HFC-23	12,400	13,856	14,600	1,456	2,200
HFC-32	677	817	771	140	94
HFC-41	116	141	135	25	19
HFC-125	3,170	3,691	3,740	521	570
HFC-134a	1,300	1,549	1,530	249	230
HFC-143a	4,800	5,508	5,810	708	1,010
HFC-152a	138	167	164	29	26
HFC-227ea	3,350	3,860	3,600	510	250
HFC-236fa	8,060	8,998	8,690	938	630
CF_4	6,630	7,349	7,380	719	750
C_2F_6	11,100	12,340	12,400	1,240	1,300
C_3F_8	8,900	9,878	9,290	978	390
c-C_4F_8	9,540	10,592	10,200	1,052	660
SF_6	23,500	26,087	24,300	2,587	800
NF_3	16,100	17,885	17,400	1,785	1,300

NC (No Change)

[a] The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

[b] The GWP values in this column are from the AR5 report but include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime.

[c] The GWP values in this column are from the AR6 report.

[d] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Including the indirect effect due to the production of CO_2 resulting from methane oxidation would lead to an increase in AR5 methane GWP values by 2 for fossil methane and is not shown in this table.

Note: Parentheses indicate negative values.

Sources: IPCC (2021), IPCC (2013), IPCC (2007), IPCC (2001), IPCC (1996).

1.2 National Inventory Arrangements

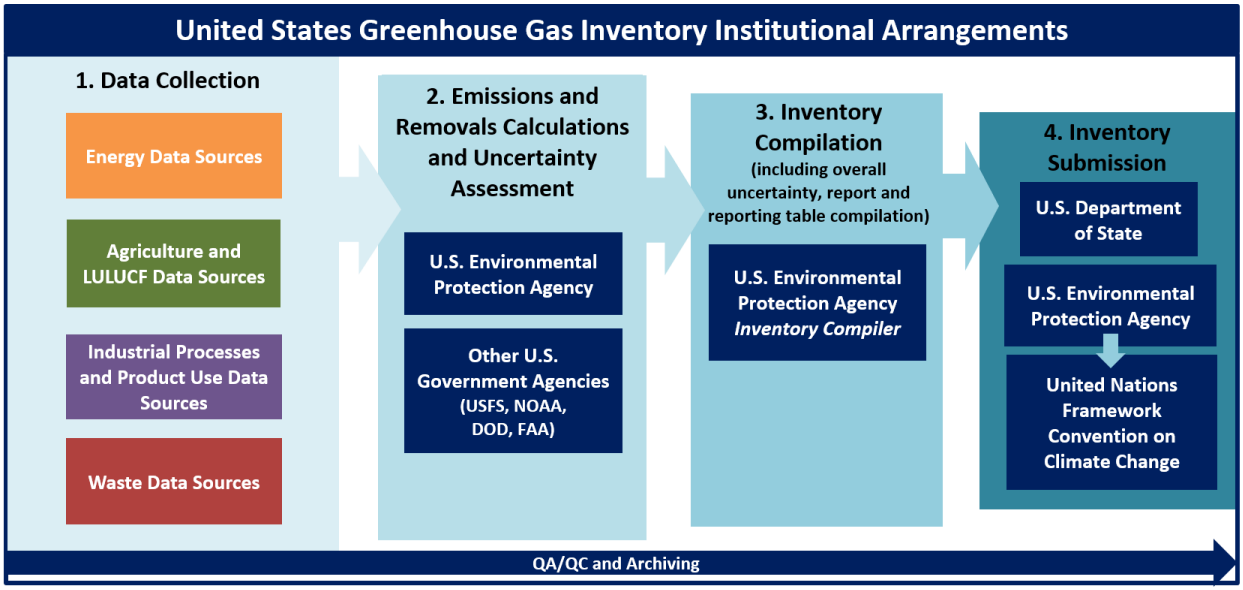
The U.S. Environmental Protection Agency (EPA), in cooperation with other U.S. government agencies, prepares the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A wide range of agencies and individuals are involved in supplying data to, planning methodological approaches and improvements, reviewing, or preparing portions of the Inventory—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

Within EPA, the Office of Atmospheric Protection (OAP) is the lead office responsible for the emission and removal calculations provided in the Inventory, as well as the completion of the National Inventory Report including the Common Reporting Tables (CRTs). EPA's Office of Transportation and Air Quality (OTAQ) and Office of Research and Development (ORD) are also involved in calculating emissions and removals for the Inventory. The U.S. Department of State (DOS) serves as the overall national focal point to the Paris Agreement and the UNFCCC, and EPA's OAP serves as the National Inventory Focal Point for this report, including responding to technical questions and comments on the U.S. Inventory. EPA staff coordinate the annual methodological choice, activity data collection, emission and removal calculations, uncertainty assessment, QA/QC processes, and improvement

planning at the individual source and sink category level. EPA's inventory coordinator manages overall compilation of the entire *Inventory* into the proper reporting format for submission under the Paris Agreement and the UNFCCC and is responsible for the synthesis of information along with the consistent application of cross-cutting IPCC good practice across the *Inventory*.

Several other government agencies contribute to the collection and analysis of the necessary underlying activity data used in the Inventory calculations via formal (e.g., interagency agreements) and informal relationships, in addition to the calculation of estimates integrated in the report (e.g., U.S. Department of Agriculture's U.S. Forest Service and Agricultural Service, National Oceanic and Atmospheric Administration, Federal Aviation Administration, and Department of Defense). Other U.S. agencies provide official data for use in the *Inventory*. The U.S. Department of Energy's Energy Information Administration provides national fuel consumption data and the U.S. Department of Defense provides data on military fuel consumption and use of bunker fuels. Other U.S. agencies providing activity data for use in EPA's emission calculations include: the U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, and the Federal Aviation Administration. Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in voluntary outreach efforts with EPA. EPA engages with agencies regularly on data needs and improvements to ensure sufficient activity collection for annual compilation of estimates. Finally, EPA as the National Inventory Focal Point, in coordination with the U.S. Department of State, officially submits the *Inventory* under the Paris Agreement and the UNFCCC each April by the reporting deadline.

Figure 1-1: National Inventory Arrangements and Process Diagram



Overview of Inventory Data Sources by Source and Sink Category

Energy	Agriculture and LULUCF	IPPU	Waste
U.S. Energy Information Administration	USDA U.S. Forest Service Forest Inventory and Analysis Program (FIA)	EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Greenhouse Gas Reporting Program (GHGRP)
U.S. Department of Commerce – Bureau of the Census	USDA Natural Resource Conservation Service (NRCS)	U.S. Geological Survey (USGS) National Minerals Information Center	EPA Office of Land and Emergency Management (OLEM)
U.S. Department of Defense – Defense Logistics Agency	USDA National Agricultural Statistics Service (NASS) and Agricultural Research Service (ARS)	American Chemistry Council (ACC)	EPA Clean Watershed Needs Survey (CWNS)
U.S. Department of Homeland Security	EPA Office of Research and Development (ORD)	American Iron and Steel Institute (AISI)	American Housing Survey
U.S. Department of Transportation - Federal Highway Administration	U.S. Fish and Wildlife Service	U.S. International Trade Commission (USITC)	Data from research studies, trade publications, and industry associations
U.S. Department of Transportation - Federal Aviation Administration	U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS)	Air-Conditioning, Heating, and Refrigeration Institute	
U.S. Department of Transportation & Bureau of Transportation Statistics	Association of American Plant Food Control Officials (AAPFCO)	Data from other U.S. government agencies, research studies, trade publications, and industry association	
U.S. Department of Labor – Mine Safety and Health Administration	National Oceanic and Atmospheric Administration (NOAA)	UNEP Technology and Economic Assessment Panel (TEAP)	
U.S. Department of Energy and its National Laboratories	EPA Office of Land and Emergency Management (OLEM)		
EPA Acid Rain Program	USDA Farm Service Agency		
EPA MOVES Model	U.S. Geological Survey (USGS)		
EPA Greenhouse Gas Reporting Program (GHGRP)	U.S. Department of the Interior (DOI) - Bureau of Land Management (BLM)		
U.S. Department of Labor – Mine Safety and Health Administration	EPA Office of Land and Emergency Management (OLEM)		
American Association of Railroads	Alaska Department of Natural Resources		
American Public Transportation Association	U.S. Department of Commerce – Bureau of the Census		
U.S. Department of Interior - Bureau of Ocean Energy Management	Data from research studies, trade publications, and industry associations		
Federal Energy Regulatory Commission			
Data from research studies, trade publications, and industry associations			

Note: This table is not an exhaustive list of all data sources.

1.3 Inventory Preparation Process

This section describes EPA's approach to preparing the annual U.S. *Inventory*, which includes both the National Inventory Document (NID) and Common Reporting Tables (CRTs). The inventory coordinator at EPA, with support from the cross-cutting compilation staff, is responsible for coordinating aggregation of all emission and removal estimates, conducting the overall uncertainty analysis of *Inventory* emissions and trends over time, and ensuring consistency and quality throughout the NID and CRTs. Emission and removal calculations, including associated uncertainty analysis for individual sources and/or sink categories are the responsibility of individual source and sink category leads, who are most familiar with each category, underlying data, and the unique national circumstances relevant to its emissions or removals profile. Using IPCC methodological decision trees and suggested good practice guidance, the individual leads determine the most appropriate methodology and collect the relevant activity data to use in the emission and removal calculations, based upon their expertise in the source or sink category, as well as coordinating with researchers and expert consultants familiar with the sources and sinks. Each year, the coordinator oversees a multi-stage process for collecting information from each individual source and sink category lead to compile all information and data for the *Inventory*.

Methodology Development, Data Collection, and Emissions and Sinks Estimation

Source and sink category leads at EPA coordinate the collection of input data (e.g., activity data and other information) and, as necessary, evaluate or develop the estimation methodology for the individual source and/or sink categories. Because EPA has been leading preparation of the *Inventory* for many years, for most source and sink categories, the methodology for the previous year is applied to the new "current" year of the *Inventory*, and inventory analysts collect any new data or update data that have changed from the previous year. If estimates for a new source or sink category are being developed for the first time, or if the methodology is changing for an existing category (e.g., the United States is implementing improvement efforts to apply a higher tiered approach for that category), then the source and/or sink category lead will develop and implement the new or refined methodology, gather the appropriate activity data and other information (e.g., emission factors or in some cases direct emission measurements) for the entire time series, and conduct any further category-specific review with involvement of relevant experts from industry, government, and universities (see Chapter 9 and Box ES-3 on EPA's approach to recalculations).

Once the methodology is in place and the data are collected, the individual source and sink category leads calculate emission and removal estimates. The individual leads then update or create the relevant national inventory document text and accompanying annexes for the *Inventory*. Source and sink category leads are also responsible for completing the relevant sectoral background tables of the CRTs, conducting quality control (QC) checks, preparing relevant category materials for QA, or expert reviews, category-level uncertainty assessments, and reviewing data for publication in EPA's GHG Data Explorer.[55]

The treatment of confidential business information (CBI) in the *Inventory* is based on EPA internal guidelines, as well as regulations[56] applicable to the data used. EPA has specific procedures in place to safeguard CBI during the inventory compilation process. When information derived from CBI data is used for development of inventory calculations, EPA procedures ensure that these confidential data are sufficiently aggregated to protect confidentiality while still providing useful information for analysis. For example, within the Energy and Industrial

[55] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

[56] 40 CFR Part 2, Subpart B titled "Confidentiality of Business Information" which is the regulation establishing rules governing handling of data entitled to confidentiality treatment. See https://www.ecfr.gov/cgi-bin/text-idx?SID=a764235c9eadf9afe05fe04c07a28939&mc=true&node=sp40.1.2.b&rgn=div6.

Processes and Product Use (IPPU) sectors, EPA has used aggregated facility-level data from the Greenhouse Gas Reporting Program (GHGRP) to develop, inform, and/or quality-assure U.S. emission estimates. In 2014, EPA's GHGRP, with industry engagement, compiled criteria that would be used for aggregating its confidential data to shield the underlying CBI from public disclosure.[57] In the *Inventory*, EPA is publishing only data values that meet the GHGRP aggregation criteria.[58] Specific uses of aggregated facility-level data are described in the respective methodological sections within those chapters. In addition, EPA uses historical data reported voluntarily to EPA via various voluntary initiatives with U.S. industry (e.g., EPA Voluntary Aluminum Industrial Partnership (VAIP)) and follows guidelines established under the voluntary programs for managing CBI.

Data Compilation and Archiving

The inventory coordinator at EPA with support from the data/document manager collects the source and sink categories' descriptive text and annexes, and also aggregates the emission and removal estimates into a summary data file that links the individual source and sink category data files together. This summary data file contains all of the essential data in one central location, in formats commonly used in the *Inventory* document. In addition to the data from each source and sink category, other national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Trends chapters of the *Inventory* report (e.g., GDP, population, energy use). Similarly, the recalculation analysis and key category analysis are completed in a separate data file based on output from the summary data file. The uncertainty estimates for each source and sink category are also aggregated into uncertainty summary data files that are used to conduct the overall *Inventory* uncertainty analysis (see Section 1.7). A Microsoft SharePoint work site, maintained within EPA's IT infrastructure by the inventory coordinator, provides a platform for facilitating collaboration on the national inventory report preparation during each compilation phase, but also the efficient storage and archiving of electronic document and data files each annual cycle. Previous final published inventories are also maintained on a report archive page on EPA's Greenhouse Gas Emissions website.[59]

National Inventory Document (NID) Preparation

The NID is compiled from the sections developed by each individual source or sink category lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions and removals from all sources and sinks discussed in the chapters. Also at this time, the Executive Summary, Introduction, Trends in Greenhouse Gas Emissions and Removals, and Recalculations and Improvements chapters are drafted, to reflect the trends and impact from improvements for the time series of the current *Inventory*. The analysis of trends necessitates gathering supplemental data, including annual climate, economic activity and gross domestic product, population, atmospheric conditions, and the annual use of electricity, energy, fossil and non-fossil fuels. Changes in these data are used to explain the trends observed in greenhouse gas emissions in the United States. Furthermore, specific factors that affect individual sectors are researched and discussed. Many of the factors that affect emissions are included in the *Inventory* document as separate analyses or side discussions in boxes within the text. Finally, the uncertainty analysis and key category analysis are compiled and updated in the report as part of final analysis steps. Throughout the report text boxes are also created to provide additional documentation (e.g., definitions) and/or examine the data aggregated in different ways than in the remainder of the document, such as a focus on transportation activities or emissions from electricity generation. The document is prepared to align with the Paris Agreement and UNFCCC reporting guidelines for National Inventory Reports while also reflecting national circumstances.

---

[57] Federal Register Notice on "Greenhouse Gas Reporting Program: Publication of Aggregated Greenhouse Gas Data." See pp. 79 and 110 of notice at https://www.gpo.gov/fdsys/pkg/FR-2014-06-09/pdf/2014-13425.pdf.

[58] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[59] See https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-archive.

Common Reporting Tables (CRTs) Compilation

The CRTs are compiled from individual time series input data sheets completed by each individual source or sink category lead, which contain emissions and/or removals and activity data, estimates, methodological and completeness notations and associated explanations. The inventory coordinator and cross-cutting compilation staff import the U.S. category and subcategory background data into the UNFCCC's Enhanced Transparency Framework Reporting Tools to export CRTs, assuring consistency and completeness across all sectoral tables. The summary reports for emissions and removals, methods, and emission factors used, the summary tables indicating completeness of estimates (i.e., notation key NE/IE tables), the recalculation tables, and the emission and removal trends tables are automatically compiled by the online reporting software and reviewed by the inventory coordinator with support from the cross-cutting compilation staff. Internal automated quality checks within the software, as well as checks by the cross-cutting and category leads, are completed for the entire time series of CRTs before submission.

QA/QC and Uncertainty

Quality assurance and quality control (QA/QC) and uncertainty analyses are guided by the QA/QC and inventory coordinators, who help maintain the QA/QC plan and the overall uncertainty analysis procedures (see sections on QA/QC and Uncertainty, below) in collaboration with the broader inventory compilation team. The QA/QC coordinator works closely with the Inventory coordinator and source and sink category leads to ensure that a consistent QA/QC plan is implemented across all inventory categories. Similarly, the inventory coordinator ensures the uncertainty analysis is implemented consistently across all categories. The inventory QA/QC plan, outlined in Section 1.6 and Annex 8, is consistent with the quality assurance procedures outlined by EPA and IPCC good practices. The QA/QC and uncertainty findings also inform overall improvement planning, and specific improvements are noted in the Planned Improvements sections of respective categories. QA processes are outlined below.

Expert, Public, and UNFCCC/Paris Reviews

The compilation of the *Inventory* includes a two-stage review or QA process, in addition to international technical expert review following submission of the report under the UNFCCC and Paris Agreement. EPA publishes responses to comments received during both expert and public reviews with the publication of the final report on its website.[60] Responses to UNFCCC and Paris reviews are included in Annex 8 of this document.

During the first stage of review, i.e., the 30-day expert review period, a first draft of updated sectoral chapters are sent to technical experts who are not directly involved in preparing estimates. The purpose of the expert review is to provide an objective review of the methodological approaches and data sources used in the current *Inventory*, especially for sources and sinks which have experienced any changes since the previous *Inventory*. Expert review follows good practices from EPA's Peer Review handbook, i.e., the review is organized by sector, and reviewers are provided a guidance memo and charge questions to facilitate their review.[61] Expert reviewers include other federal agency staff, researchers, industry experts, and others who have technical knowledge of the data, industry, and methods. EPA reviews and updates expert participation and outreach on an annual basis prior to each expert review cycle. Experts are identified in various ways; for example, many reach out to EPA with technical feedback and are added to the expert reviewer list. Reviewers are also identified through direct outreach by inventory staff based on expertise. Currently, EPA's expert list includes nearly 300 experts across all sectors. Once comments are received, they are reviewed by the source or sink lead and addressed in several ways. For example, comments suggesting methodological clarifications may be incorporated into methodological discussions prior to the next

[60] See https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

[61] See https://www.epa.gov/osa/peer-review-handbook-4th-edition-2015.

review phase, while comments citing new literature or data will be noted for review as part of planned improvements.

Following expert review, a second draft of the document, including cross-cutting synthesis chapters, is released for a 30-day public review through a notice in the U.S. Federal Register. The entire draft *Inventory* document is published on the EPA website. The public review period is open to the entire U.S. public. Comments are submitted and tracked using an online electronic docket that is accessible to the general public as well. Similar to expert review, some comments received may require further discussion with commenters, other experts and/or additional research. Specific *Inventory* improvements requiring further analysis as a result of comments are noted in the relevant category's Planned Improvement section.

As mentioned above, following completion and submission of the report under the UNFCCC and the Paris Agreement, the report also undergoes review by an international team of independent experts for adherence to UNFCCC/Paris reporting guidelines and consistency with IPCC methodological guidance.[62] Feedback from all review processes that contribute to improving inventory quality over time are described within each planned improvement section and further in Annex 8. See also the Improvement Planning process discussed below.

Final Submittal and Publication under the Paris Agreement and the UNFCCC

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final NIR, which includes the NID and the accompanying CRTs for electronic reporting. Prior to submission, EPA's Office of Atmospheric Protection briefs senior leadership on reporting findings and improvements since the previous report, along with an overview of feedback from the expert and public review processes.

EPA, as the National Inventory Focal Point, sends the official submission of the U.S. *Inventory* under the Paris Agreement and the UNFCCC using the UN's reporting software, coordinating with the U.S. Department of State, the overall UNFCCC focal point. Concurrently, the report is also published on EPA's website.[63] On EPA's website, users can also visualize and download the current time-series estimates from the GHG Inventory Data Explorer Tool,[64] and also download more detailed data presented in tables within the report and report annex in CSV format.

Improvement Planning

Each year, several emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised, through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement*, which state, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is *good practice* to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors." The EPA's OAP coordinates improvement planning across all sectors and also cross-cutting analyses based on annual review and input from the technical teams leading compilation of each sector's estimates, including

[62] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/review-process.

[63] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[64] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

continuous improvements to the overall data and document compilation and QA/QC processes. Planned improvements are identified through QA/QC processes (including completeness checks), the key category analysis, and the uncertainty analysis. The inventory coordinator, with input from EPA source and sink category leads, maintains a log of all planned improvements, by sector and cross-cutting, tracking the category significance, specific category improvement, prioritization, anticipated time frame for implementation of each proposed improvement, and status of progress in implementing improvement. Improvements for significant or key categories are usually prioritized across all improvements unless effort would require disproportionate levels of effort and resources relative to improvements for other key categories to address.

1.4 Methodology and Data Sources

Emissions and removals of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and its supplements and refinements. To a great extent, this report makes use of published official economic and physical statistics for activity data, emission factors and other key parameters as inputs to the methods applied. Depending on the category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, or commodity produced, etc. Emission factors are factors that relate quantities of emissions to an activity. For more information on data sources see Section 1.2 above, Box 1-1 on use of GHGRP data, and categories' methodology sections for more information on other data sources. In addition to official statistics, the report utilizes findings from academic studies, trade association surveys and statistical reports, along with expert judgment, consistent with the *2006 IPCC Guidelines*.

The methodologies provided in the *2006 IPCC Guidelines* represent foundational methodologies for a variety of source and sink categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses those IPCC methodologies when applicable, and supplements them with refined guidance, other available country-specific methodologies and data where possible (e.g., EPA's GHGRP). For example, as noted earlier in this chapter, this report does apply recent supplements and refinements to *2006 IPCC Guidelines* in estimating emissions and removals from coal mining, wastewater treatment and discharge, low voltage anode effects (LVAE) during aluminum production, drained organic soils, and management of wetlands, including flooded lands. Choices made regarding the methodologies and data sources used are provided in the Methodology and Time-Series Consistency discussion of each category within each sectoral chapter of the report, applying higher tiered methods when feasible, especially for key categories consistent with methodological decision trees. Where additional detail is helpful and necessary to explain methodologies and data sources used to estimate emissions, complete documentation is provided in the annexes as indicated in the methodology sections of those respective source categories (e.g., Annex 3.13 for forest land remaining forest land and land converted to forest land). Methods used for key categories (discussed below) are summarized in Annex 1.

1.5 Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019) define key categories as "inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the level of uncertainty in emissions or removals. Whenever the term *key category* is used, it

includes both source and sink categories."[65] A key category analysis identifies source or sink categories for focusing efforts to improve overall Inventory quality, including additional review when feasible.

The *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement* (2019) define several approaches, both quantitative and qualitative, to conduct a key category analysis and identify key categories both in terms of absolute level and trend, along with consideration of uncertainty. This report employs all approaches to identify key categories for the United States. The first approach, Approach 1, identifies significant or key categories without considering uncertainty in its calculations. An Approach 1 level assessment identifies all source and sink categories that cumulatively account for 95 percent of total level, i.e., total emissions (gross) in a given year when assessed in descending order of absolute magnitude. The level analysis was performed twice, including and excluding sources and sinks from the land use, land-use change, and forestry (LULUCF) sector categories. Similarly, an Approach 1 trend analysis can identify categories with trends that significantly influence overall trends by identifying all source and sink categories that cumulatively account for 95 percent of the sum all the trend assessments (e.g., percent change relative to national trend) when sorted in descending order of absolute magnitude.

The next method, Approach 2, was then implemented to identify any additional key categories not already identified from the Approach 1 level and trend assessments by considering uncertainty. The Approach 2 analysis differs from Approach 1 by incorporating each category's uncertainty assessments in its calculations and was also performed twice, including and excluding LULUCF categories. An Approach 2 level assessment identifies all sources and sink categories that cumulatively account for 90 percent of the sum of all level assessments when sorted in descending order of magnitude. Similarly, an Approach 2 trend analysis can identify categories whose trends contribute significantly to overall trends weighing the relative trend difference with the category's relative uncertainty assessment for 2022.

For 2022, based on the key category analysis, excluding the LULUCF sector and uncertainty, 34 categories accounted for 95 percent of emissions. Four categories account for 55 percent of emissions: CO_2 from road transport-related fuel combustion, CO_2 from coal-fired electricity generation, CO_2 from gas fired electricity generation, and CO_2 from gas-fired industrial processes. When considering uncertainties, additional categories such as emissions from substitutes for ozone depleting substances in aerosols were also identified as a key category. In the trend analysis, 32 categories were identified as key categories, and when considering uncertainties, 7 additional categories were identified as key. The trend analysis shows that CO_2 emissions from coal-fired electricity generation, in addition to CO_2 from gas fired electricity generation, CO_2 from road transport related combustion, and HFC and PFC emissions from substitutes for ozone depleting substances in the refrigeration and air conditioning sector are also significant with respect to trends over the time series.

When considering the contribution of the LULUCF sector to 2022 emissions and removals, 42 categories accounted for 95 percent of emissions and sinks, with the most significant category from LULUCF being net CO_2 emission from forest land remaining forest land. When considering uncertainties and the contribution of the LULUCF sector, additional categories such as net CO_2 emissions from grassland remaining grassland were also identified as a key category. In the trend analysis, 40 categories were identified as key, and when considering uncertainties, 2 additional categories were identified as key.

Finally, in addition to conducting Approach 1 and 2 level and trend assessments as described above, a qualitative assessment of the source and sinks categories was conducted to capture any additional key categories that were not identified using the previously described quantitative approaches. For this *Inventory*, no additional categories were identified using qualitative criteria recommend by IPCC, but EPA continues to review its qualitative assessment on an annual basis. Find more information on the key category analysis, including the approach to disaggregation of inventory estimates, see Annex 1 to this report.

[65] See Chapter 4 Volume 1, "Methodological Choice and Identification of Key Categories" in IPCC (2006) and IPCC (2019). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Table 1-4: Summary of Key Categories for the United States (1990 and 2022) by Sector

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Energy										
1.A.3.b Transportation: Road	CO_2	◉	•	◉	•	◉	•	◉	•	1,438.1
1.A.1 Stationary Combustion - Coal - Electricity Generation	CO_2	◉	•	◉	•	◉	•	◉	•	851.5
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	CO_2	◉	•	◉	•	◉	•		•	659.3
1.A.2 Stationary Combustion - Natural Gas - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	510.4
1.A.4.b Stationary Combustion - Natural Gas - Residential	CO_2	◉	•	◉	•	◉	•	◉		272.0
1.A.2 Stationary Combustion - Oil - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	247.6
1.A.4.a Stationary Combustion - Natural Gas - Commercial	CO_2	◉	•	◉	•	◉	•	•	•	192.3
1.A.3.a Transportation: Aviation	CO_2	◉	•	◉	•	◉		◉		165.6
1.A.5 Non-Energy Use of Fuels	CO_2	◉		◉		◉	•	◉		102.8
1.A.3.e Transportation: Other	CO_2	◉	•	◉	•		•			69.3
1.A.4.a Stationary Combustion - Oil - Commercial	CO_2	◉	•	◉	•					65.1
1.A.4.b Stationary Combustion - Oil - Residential	CO_2	◉	•	◉	•					62.1

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.2 Stationary Combustion - Coal - Industrial	CO_2	◉	•	◉	•	◉	•	○	•	43.0
1.A.3.d Transportation: Domestic Navigation	CO_2	◉		◉						40.9
1.B.2 Natural Gas Systems	CO_2	◉		◉						36.5
1.A.3.c Transportation: Railways	CO_2	◉		◉						32.5
1.B.2 Petroleum Systems	CO_2	•	•	•	•		•		•	22.0
1.A.1 Stationary Combustion - Oil - Electricity Generation	CO_2	◉	•	◉	•	○	•		•	20.5
1.A.5 Stationary Combustion - Oil - U.S. Territories	CO_2	○		○						17.0
1.A.5.b Transportation: Military	CO_2		•		•					4.8
1.A.4.a Stationary Combustion - Coal - Commercial	CO_2		•		•					1.4
1.A.4.b Stationary Combustion - Coal - Residential	CO_2						•			NO
1.B.2 Natural Gas Systems	CH_4	◉	•	◉	•	◉	•	◉	•	173.1
1.B.1 Fugitive Emissions from Coal Mining	CH_4	◉	•	◉	•	◉	•	◉	•	43.6
1.B.2 Petroleum Systems	CH_4	◉	•	◉	•	◉	•	◉		39.6
1.B.2 Abandoned Oil and Natural Gas Wells	CH_4					◉		◉		8.5
1.A.4.b Stationary Combustion - Residential	CH_4					◉	•	◉	•	4.3
1.A.1 Stationary Combustion - Coal - Electricity Generation	N_2O					◉		•		18.2
1.A.3.b Transportation: Road	N_2O	○	•	○	•					8.9

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	N_2O						•			3.4
Industrial Processes and Product Use										
2.A.1 Cement Production	CO_2	◉		◉	•					41.9
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CO_2	◉	•	◉	•	◉	•	○	•	40.7
2.B.8 Petrochemical Production	CO_2	◉	•	◉	•					28.8
2.B.3 Adipic Acid Production	N_2O		•		•					2.1
2.F.1 Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	144.6
2.F.4 Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs		•		•	•	•	•	•	17.0
2.F.2 Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					11.7
2.B.9 Fluorochemical Production	PFCs, HFCs, SF_6, NF_3	○	•	○	•	○	•	○	•	7.8
2.G Electrical Equipment	PFCs, SF_6	○	•	○	•		•		•	5.1
2.C.3 Aluminum Production	PFCs	○	•	○	•					0.8
Agriculture										
3.A.1 Enteric Fermentation: Cattle	CH_4	◉	•	◉	•	◉	•	◉	•	185.9
3.B.1 Manure Management: Cattle	CH_4	•	•	•	•	•	•		•	37.7
3.B.4 Manure Management: Other Livestock	CH_4	◉		◉		•				27.0
3.C Rice Cultivation	CH_4	◉		•		◉		◉		18.9

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
3.D.1 Direct Emissions from Agricultural Soil Management	N_2O	◉		◉		◉		◉		262.5
3.D.2 Indirect Emissions from Applied Nitrogen	N_2O	◉		◉		◉	•	◉		28.3
Waste										
5.A Commercial Landfills	CH_4	◉	•	◉	•	◉	•	◉	•	100.9
5.A Industrial Landfills	CH_4	•		•		•	•			18.9
5.D Domestic Wastewater Treatment	CH_4					○				13.6
5.D Domestic Wastewater Treatment	N_2O	•		•		◉	•	◉	•	21.4
Land Use, Land-Use Change, and Forestry										
4.E.2 Net Emissions from Land Converted to Settlements	CO_2			◉	•			◉	•	68.2
4.B.2 Net Emissions from Land Converted to Cropland	CO_2			◉	•			◉	•	35.1
4.C.2 Net Emissions from Land Converted to Grassland	CO_2			◉	•			◉	•	25.6
4.C.1 Net Emissions from Grassland Remaining Grassland	CO_2			○	•			◉	•	13.4
4.B.1 Net Removals from Cropland Remaining Cropland	CO_2			•	•			◉	•	(31.7)
4.A.2 Net Removals from Land Converted to Forest Land	CO_2			◉				◉		(100.3)
4.E.1 Net Removals from Settlements Remaining Settlements	CO_2			◉	•			◉	•	(134.8)

CRT Code and Source/Sink Category	Greenhouse Gas	Approach 1[a]				Approach 2 (includes uncertainty)[a]				2022 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
4.A.1 Net Removals from Forest Land Remaining Forest Land	CO_2			◉	•			◉	•	(787.0)
4.D.1 Flooded Lands Remaining Flooded Lands	CH_4			◉						44.2
Subtotal of Key Categories Without LULUCF[b]										**6,169.7**
Total Gross Emissions Without LULUCF										**6,343.2**
Percent of Gross Total Without LULUCF										**97%**
Subtotal of Key Categories With LULUCF[c]										**5,285.4**
Total Net Emissions With LULUCF										**5,488.9**
Percent of Net Total With LULUCF										**96%**

NO (Not Occurring)

[a] Symbols correspond to the year(s) in which a category is key: 1990 = ○; 2022 = •; 1990 and 2022 = ◉.

[b] Subtotal includes key categories from Level Approach 1 Without LULUCF, Level Approach 2 Without LULUCF, Trend Approach 1 Without LULUCF, and Trend Approach 2 Without LULUCF.

[c] Subtotal includes key categories from Level Approach 1 With LULUCF, Level Approach 2 With LULUCF, Trend Approach 1 With LULUCF, and Trend Approach 2 With LULUCF.

Note: Parentheses indicate negative values (or sequestration).

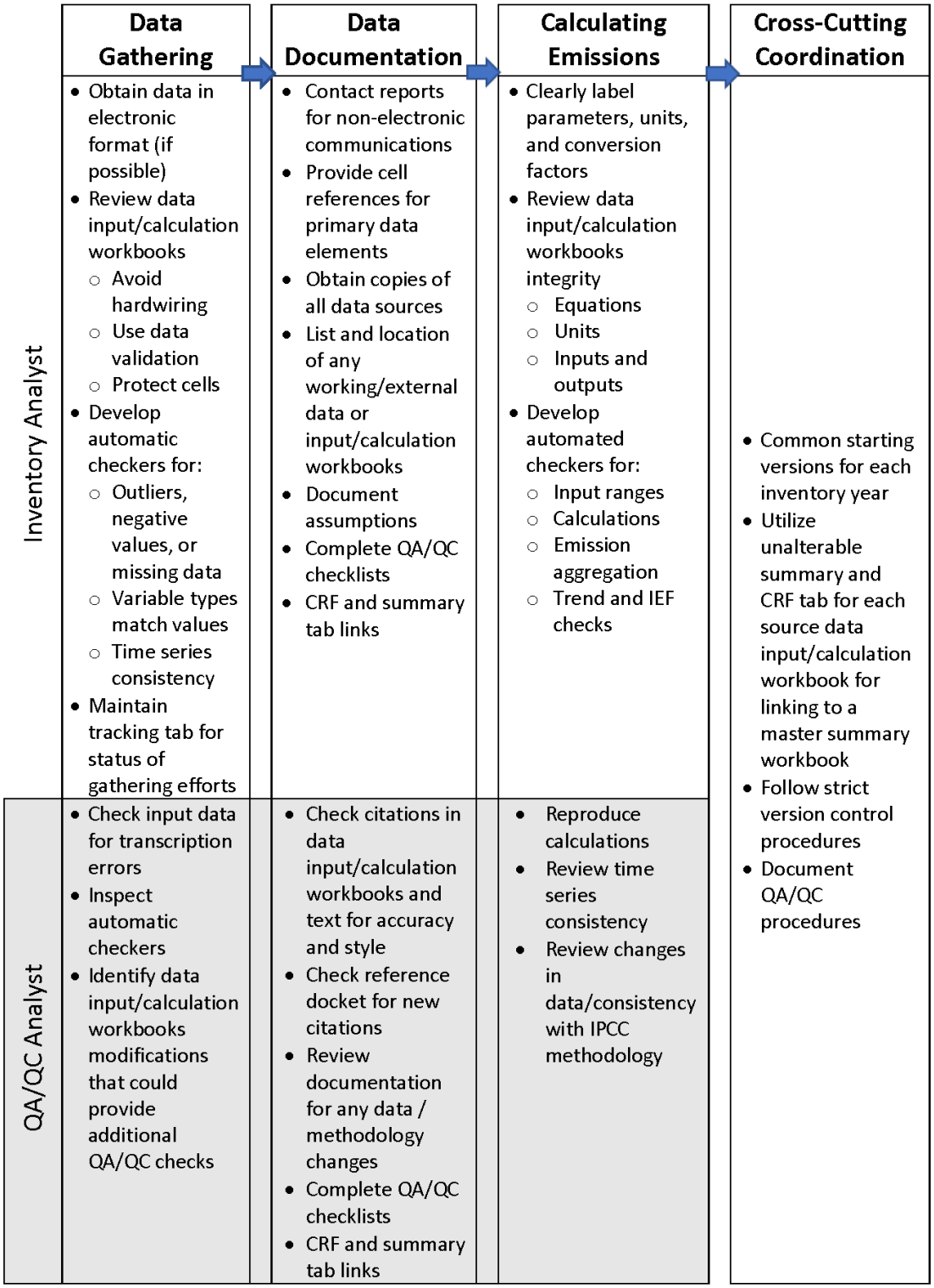
1.6 Quality Assurance and Quality Control (QA/QC)

As part of efforts to achieve its stated goals for inventory quality, transparency, and credibility, the United States has developed a quality assurance and quality control plan designed to check, document, and improve the quality of its inventory over time. QA/QC activities on the *Inventory* are undertaken within the framework of the U.S. *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC plan) *for the U.S. Greenhouse Gas Inventory: Procedures Manual for QA/QC and Uncertainty Analysis*.

Key attributes of the QA/QC plan are summarized in Figure 1-2. These attributes include:

- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving QA/QC implementation and related information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures:* guidance on application of QA/QC procedures throughout the whole Inventory development process from initial data collection, through preparation of the emission and removal estimates, to publication of the *Inventory,* consistent with the *2006 IPCC Guidelines*.
- *Quality Assurance (QA):* process for implementing expert and public reviews for both the inventory estimates and the Inventory report (which is the primary vehicle for disseminating the results of the inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the QA good practice and the *2006 IPCC Guidelines* (IPCC 2006). See Section 1.3 for more details on these QA processes.
- *Quality Control (QC)*: application of *General (Tier 1) and Category-specific (Tier 2)* quality controls and checks, as recommended by *2006 IPCC Guidelines* (IPCC 2006), along with consideration of secondary data and category-specific checks (additional Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates, which provides for more structured communication and integration with the suppliers of secondary information
- *General (Tier 1) and Category-specific (Tier 2) Checks:* quality controls and checks, as recommended by *IPCC Good Practice Guidance* and *2006 IPCC Guidelines* (IPCC 2006)
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations which provide for continual data quality improvement and guided research efforts moving forward.
- *Multi-Year Implementation*: tracking the application of more involved QA/QC procedures which may take more than one cycle to fully implement, especially for category-specific QC, prioritizing key categories in conjunction with improvement planning (see Section 1.3).
- *Interaction and Coordination:* promoting communication within the EPA, across federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying data or preparing estimates for the *Inventory*. The QA/QC Management Plan itself is intended to be revised and reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary.

Figure 1-2: Summary of Key QC Processes from U.S. QA/QC Plan



Box 1-3: Examples of Verification Activities

Consistent with IPCC guidance for national greenhouse gas inventories, verification activities include comparisons with emission or removal estimates prepared by other bodies and comparisons with estimates derived from fully independent assessments, e.g., atmospheric concentration measurements. Verification activities provide information to improve inventories and are part of the overall QA/QC system.

Use of Lower Tier Methods. The Paris Agreement/UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology for purposes of verification. This estimation method uses alternative methodologies and different data sources than those contained in that section of the Energy chapter. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex 4 of this report). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

Use of Ambient Measurements Systems for Validation of Emission Inventories. In following the Paris Agreement and UNFCCC reporting requirements to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally accepted methods provided by the IPCC.[66] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[67] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the *Inventory* in a manner consistent with this *Inventory* report's transparency of its calculation methodologies, and the ability of inverse modeling to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that emission estimates derived from atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6). Further, it identified fluorinated gases as particularly suitable for such comparisons due their limited natural sources, their generally long atmospheric lifetimes, and well-understood loss mechanisms, which makes it relatively more straightforward to model their emission fluxes from observed mass quantities. Unlike emissions of CO_2, CH_4, and N_2O, emissions of fluorinated greenhouse gases are almost exclusively anthropogenic, meaning that the fluorinated greenhouse gas emission sources included in this Inventory account for the majority of the total U.S. emissions of these gases detectable in the atmosphere. This evaluation approach is also useful for gases and sources with larger uncertainties in available bottom-up inventory methods and data, such as emissions of CH_4, which are primarily from uncertain biological (e.g., enteric fermentation) and fugitive (e.g., natural gas production) activities.

In this *Inventory*, EPA includes the results from current and previous comparisons between fluorinated gas

[66] See http://www.ipcc-nggip.iges.or.jp/public/index.html.

[67] See http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf.

emissions inferred from atmospheric measurements and fluorinated gas emissions estimated based on bottom-up measurements and modeling. These comparisons, performed for HFCs and SF_6 respectively, are described under the QA/QC and Verification discussions in Chapter 4, Sections 4.25 Substitution of Ozone Depleting Substances and 4.26 Electrical Equipment in the IPPU chapter of this report.

Consistent with the *2019 Refinement*, a key element to facilitate such comparisons is a spatially-explicit (or gridded) emissions inventory as an input to inverse modeling. To improve the ability to compare methane emissions from the national-level greenhouse gas inventory with observation-based emission estimates, a team of researchers from U.S. EPA, SRON Netherlands Institute for Space Research, Harvard University, and Lawrence Berkely National Laboratory developed a time series of annual anthropogenic methane emissions maps with 0.1° x 0.1° (~10km x 10km) spatial resolution and monthly temporal resolution for the contiguous United States.[68] The gridded methane inventory is designed to be consistent with the *U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates, which presents national totals for different source types.[69] The development of this gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to use of atmospheric concentration measurement data for comparison with Inventory data, information from top-down studies is directly incorporated in the Natural Gas Systems calculations to quantify emissions from certain well blowout events.

In addition, based on the national QA/QC plan for the *Inventory*, some sector, subsector and category-specific QA/QC and verification checks have been applied. These checks follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific documentation and data files associated with individual sources. For each greenhouse gas emissions source or sink category included in this *Inventory*, a minimum of general or Tier 1 QC analysis has been undertaken. Where QC activities for a particular category go beyond the minimum general checks and include category-specific checks (Tier 2) or include verification, further explanation is provided within the respective source or sink category text. Similarly, responses or updates based on comments from the expert, public and the international technical expert reviews (e.g., UNFCCC) are also addressed within the respective source or sink category sections in each sectoral chapter and Annex 8.

The quality control activities described in the U.S. QA/QC plan occur throughout the inventory process; QA/QC is not separate from, but is an integral part of, preparing the *Inventory*. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs during the expert review and the public review, in addition to the UNFCCC expert technical review. While all phases significantly contribute to improving inventory quality, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of the inventory methods and underlying input data sources.

The QA/QC plan guides the process of ensuring inventory quality by describing data and methodology checks, developing processes governing peer review and public comments, and developing guidance on conducting an analysis of the uncertainty surrounding the emission and removal estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

[68] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

[69] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

1.7 Uncertainty Analysis

Emissions and removals calculated for the U.S. Inventory reflect best estimates for greenhouse gas source and sink categories in the United States and are continuously revised and improved as new information becomes available. Uncertainty assessment is an essential element of a complete and transparent emissions inventory because it helps inform and prioritize Inventory improvements. For the U.S. Inventory, uncertainty analyses are conducted for each source and sink category as well as for the uncertainties associated with the overall emission (current and base year) and trends estimates. These analyses reflect the quantitative uncertainty in the emission (and removal) estimates associated with uncertainties in their input parameters (e.g., activity data and EFs) and serve to evaluate the relative contribution of individual input parameter uncertainties to the overall Inventory, its trends, and each source and sink category.

The overall level and trend uncertainty estimates for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology (assuming a Normal distribution for Approach 1 estimates), which employs a Monte Carlo stochastic simulation technique. The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for both individual and combined source categories. Approach 2 quantifies uncertainties based on a distribution of emissions (or removals), built-up from repeated calculations of emission estimation models and the underlying input parameters, randomly selected according to their known distributions. Approach 2 methodology is applied to each individual source and sink category wherever data and resources are permitted and is also used to quantify the uncertainty in the overall Inventory and its Trends. Source and sink chapters in this report provide additional details on the uncertainty analysis conducted for each source and sink category. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the overall emission (base and current year) and trends estimates. Consistent with IPCC (IPCC 2006), the United States has ongoing efforts to continue to improve the overall Inventory uncertainty estimates presented in this report.

The United States has also implemented many improvements over the last several years to reduce uncertainties across the source and sink categories and improve Inventory estimates. These improvements largely result from new data sources that provide more accurate data and/or increased data coverage, as well as methodological improvements. Following IPCC good practice, additional efforts to reduce Inventory uncertainties can occur through efforts to incorporate excluded emission and sink categories (see Annex 5), improve estimation methods, and collect more detailed, measured, and representative data. Individual category chapters and Annex 7 both describe current ongoing and planned Inventory and uncertainty analysis improvements. Consistent with IPCC (2006), the United States has ongoing efforts to continue to improve the category-specific uncertainty estimates presented in this report, largely prioritized by considering improvements categories identified as significant by the Key Category Analysis.

Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions in 1990 (base year) and 2022 are shown below in Table 1-5 and Table 1-6, respectively. The overall uncertainty surrounding the Total Net Emissions is estimated to be -6 to +6 percent in 1990 and -5 to +6 percent in 2022. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -3 to +4 percent in 1990 and -2 to +4 percent in 2022.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty for 1990 (MMT CO_2 Eq. and Percent)

Gas	1990 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Greenhouse Gas Estimate[a] (%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,131.6	5,008.2	5,348.2	-2%	4%	5,098.2	88.0
CH_4[d]	871.7	731.3	948.4	-16%	9%	701.5	56.3
N_2O[d]	408.2	349.7	513.0	-14%	26%	434.8	41.6
PFC, HFC, SF_6, and NF_3[d]	125.5	108.6	152.9	-13%	22%	207.3	11.6
Total Gross Emissions	**6,536.9**	**6,354.3**	**6,792.8**	**-3%**	**4%**	**6,441.8**	**113.3**
LULUCF Emissions[e]	57.9	55.2	61.9	-5%	7%	68.7	1.7
LULUCF Carbon Stock Change Flux[f]	(1,034.7)	(1,296.1)	(845.3)	25%	-18%	(957.3)	116.7
LULUCF Sector Net Total[g]	**(976.7)**	**(1,237.7)**	**(787.8)**	**27%**	**-19%**	**(888.6)**	**116.7**
Net Emissions (Sources and Sinks)	**5,560.2**	**5,247.0**	**5,882.2**	**-6%**	**6%**	**5,553.3**	**161.4**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 1990.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 1-6: Estimated Overall Inventory Quantitative Uncertainty for 2022 (MMT CO_2 Eq. and Percent)

Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Greenhouse Gas Estimate[a] (%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,053.0	4,937.3	5,257.7	-2%	4%	5,095.2	81.9
CH_4[d]	702.4	604.3	803.1	-14%	14%	703.8	52.0
N_2O[d]	389.7	324.6	490.2	-17%	26%	399.5	42.3
PFC, HFC, SF_6, and NF_3[d]	198.1	182.8	217.5	-8%	10%	199.5	9.0

Total Gross Emissions	**6,343.2**	**6,190.3**	**6,604.8**	**-2%**	**4%**	**6,397.9**	**106.3**
LULUCF Emissions[e]	67.5	64.3	73.2	-5%	8%	68.6	2.3
LULUCF Carbon Stock Change Flux[f]	(921.8)	(1,158.6)	(748.7)	26%	-19%	(957.5)	105.3
LULUCF Sector Net Total[g]	**(854.3)**	**(1,090.3)**	**(680.5)**	**28%**	**-20%**	**(888.8)**	**105.3**
Net Emissions (Sources and Sinks)	**5,488.9**	**5,216.2**	**5,801.9**	**-5%**	**6%**	**5,509.0**	**150.6**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 2022.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The uncertainty for 2022 is similar to the uncertainty for 1990, though slightly lower. There have been some improvements in significant categories which do not necessarily reduce uncertainties as also acknowledged in the IPCC 2006 IPCC GL, p. 3.13 (e.g., improvements to estimates for Agricultural Soil Management over time, implications of methodological choice). For example, the 95 percent uncertainty bounds for nitrous oxide emissions from Agricultural Soil Management were increased from –25 percent to 29 percent in 1990 to –30 percent to 72 percent in 2022. Methodological and data quality improvements were also made for HFCs, PFCs, SF_6 and NF_3 this year but the uncertainties for these sources also slightly increased, better representing the limitations of existing emissions estimates. The methods and data for fossil fuel combustion categories, the most significant source, has not changed significantly and neither have uncertainties. It is also worth noting that some of the improvements to shift to use of GHGRP have been in less significant categories within the inventory (e.g., for IPPU). So, the overall uncertainty for latest year reflects these offsetting effects and trends within the uncertainty assessment.

In addition to the estimates of uncertainty associated with the current and base year estimates, Table 1-7 presents the estimates of inventory trend uncertainty. The *2006 IPCC Guidelines* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2022) *Inventory* estimates. However, for purposes of understanding the concept of trend uncertainty, the trend is defined in this Inventory as the percentage change in the gross emissions (or net emissions) estimated for the current year, relative to the gross emission (or net emissions) estimated for the base year. The uncertainty associated with this trend is referred to as trend uncertainty and is reported as between -8 and 8 percent at the 95 percent confidence level between 1990 and 2022. This indicates a range of approximately -8 percent below and 8 percent above the trend estimate of -1.3 percent. See Annex 7 for trend uncertainty estimates for individual source and sink categories by gas.

Table 1-7: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas	Base Year Emissions[a]	2022 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO_2 Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	5,131.6	5,053.0	-2%	-6%	3%
CH_4	871.7	702.4	-19%	-32%	2%
N_2O	408.2	389.7	-5%	-30%	51%
HFCs, PFCs, SF_6, and NF_3	125.5	198.1	58%	32%	95%
Total Gross Emissions[c]	**6,536.9**	**6,343.2**	**-3%**	**-7%**	**3%**
LULUCF Emissions[d]	57.9	67.5	17%	6%	30%
LULUCF Carbon Stock Change Flux[e]	(1,034.7)	(921.8)	-11%	-35%	21%
LULUCF Sector Net Total[f]	**(976.7)**	**(854.3)**	**-13%**	**-37%**	**21%**
Net Emissions (Sources and Sinks)[c]	**5,560.2**	**5,488.9**	**-1.3%**	**-8%**	**8%**

[a] Base Year is 1990 for all sources.

[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5th percentile value and the upper bound corresponding to 97.5th percentile value.

[c] Totals exclude emissions for which uncertainty was not quantified.

[d] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N_2O emissions from forest soils and settlement soils.

[e] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[f] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

1.8 Completeness

This report, along with its accompanying CRTs, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2022. This report is intended to be comprehensive and includes the vast majority of emissions and removals identified as anthropogenic, consistent with IPCC methods and the Paris Agreement and UNFCCC reporting guidelines. In general, sources or sink categories not accounted for in this *Inventory* are excluded because they are not occurring in the United States and its territories, or because data are unavailable to develop an estimate and/or the categories were determined to be insignificant[70] in terms of overall national emissions per the Paris Agreement and UNFCCC reporting guidelines.

The United States is continually working to improve upon the understanding of such sources and sinks currently not included and seeking to find the data required to estimate related emissions and removals, focusing on categories that are anticipated to be significant. See Chapter 9 on Improvements and Recalculations for more

[70] See paragraph 32 in the Annex to Decision18/CMA.1 of the Paris Agreement reporting guidelines on national inventories that state "…emissions from a category should only be considered insignificant if the likely level of emissions is below 0.05 per cent of the national total GHG emissions, excluding LULUCF, or 500 kilotonnes of carbon dioxide equivalent (kt CO_2 eq), whichever is lower. The total national aggregate of estimated emissions for all gases from categories considered insignificant shall remain below 0.1 per cent of the national total GHG emissions, excluding LULUCF. Parties should use approximated activity data and default IPCC emission factors to derive a likely level of emissions for the respective category."

information on completeness and improvements implemented this cycle. As such improvements are implemented, new emission and removal estimates are quantified and included in the *Inventory*, improving completeness of national estimates. For a list of sources and sink categories not included and more information on significance of these categories, see Annex 5 and the respective category sections in each sectoral chapter of this report.

1.9 Organization of Report

In accordance with the Paris Agreement and UNFCCC reporting guidelines, this *Inventory* is grouped into five sector-specific chapters consistent with the Paris Agreement Common Reporting Tables (CRT),[71] listed below in Table 1-8. In addition, the U.S. *Inventory* submission includes chapters on Trends in Greenhouse Gas Emissions, Other information, and Recalculations and Improvements to be considered consistent with the suggested outline or national inventory documents submitted under the Paris Agreement and UNFCCC.

Table 1-8: CRT/IPCC Sector Descriptions

Chapter (CRT and UNFCCC/IPCC Sector)	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels.
Industrial Processes and Product Use	Emissions resulting from industrial processes and product use of greenhouse gases.
Agriculture	Emissions from agricultural activities except fuel combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, and emissions of CH_4, and N_2O from land use, land-use change, and forestry.
Waste	Emissions from waste management activities.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/CRT/IPCC Sector: Overview of emissions and trends for each CRT/IPCC defined sector.

CRT Source or Sink Category: Description of category pathway and emission/removal trends based on IPCC methodologies, consistent with the Paris Agreement and UNFCCC reporting guidelines.

Methodology and Time-Series Consistency: Description of analytical methods (e.g., from *2006 IPCC Guidelines,* or country-specific methods) employed to produce emission estimates and identification of data references, primarily for activity data and emission factors, and a discussion of time-series consistency.

Uncertainty: A discussion and quantification of the uncertainty in emission estimates.

QA/QC and Verification: A discussion on steps taken to QA/QC and verify the emission estimates, consistent with the U.S. QA/QC plan, and any key QC findings.

Recalculations Discussion: A discussion of any data or methodological changes that necessitate a recalculation of previous years' emission estimates, and the impact of the recalculation on the emission estimates, if applicable.

Planned Improvements: A discussion on any category-specific planned improvements, if applicable.

[71] See paragraph 50 in the Annex to Decision 18/CMA.1

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-9.

Table 1-9: List of Annexes

ANNEX 1 Key Category Analysis	
ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion	
2.1.	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
2.2.	Methodology for Estimating the Carbon Content of Fossil Fuels
2.3.	Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels
ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories	
3.1.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion
3.2.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
3.3.	Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption
3.4.	Methodology for Estimating CH_4 Emissions from Coal Mining
3.5.	Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
3.6.	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
3.7.	Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
3.8.	Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
3.9.	Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
3.10.	Methodology for Estimating CH_4 Emissions from Enteric Fermentation
3.11.	Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
3.12.	Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)
3.13.	Methodology for Estimating Net Carbon Stock Changes in Forest Land Remaining Forest Land and Land Converted to Forest Land
3.14.	Methodology for Estimating CH_4 Emissions from Landfills
ANNEX 4 IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion	
ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included	
ANNEX 6 Additional Information	
6.1.	Global Warming Potential Values
6.2.	Ozone Depleting Substance Emissions
6.3.	Greenhouse Gas Precursors: Mapping of NEI categories to the Inventory
6.4.	Constants, Units, and Conversions
6.5.	Chemical Formulas
ANNEX 7 Uncertainty	
7.1.	Overview
7.2.	Methodology and Results
7.3.	Reducing Uncertainty
7.4.	Planned Improvements
7.5.	Additional Information on Uncertainty Analyses by Source
ANNEX 8 QA/QC Procedures	
8.1.	Background
8.2.	Purpose
8.3.	Assessment Factors
8.4.	Responses During the Review Process
ANNEX 9 Use of Greenhouse Gas Reporting Program (GHGRP) in Inventory	

2. Trends in Greenhouse Gas Emissions and Removals

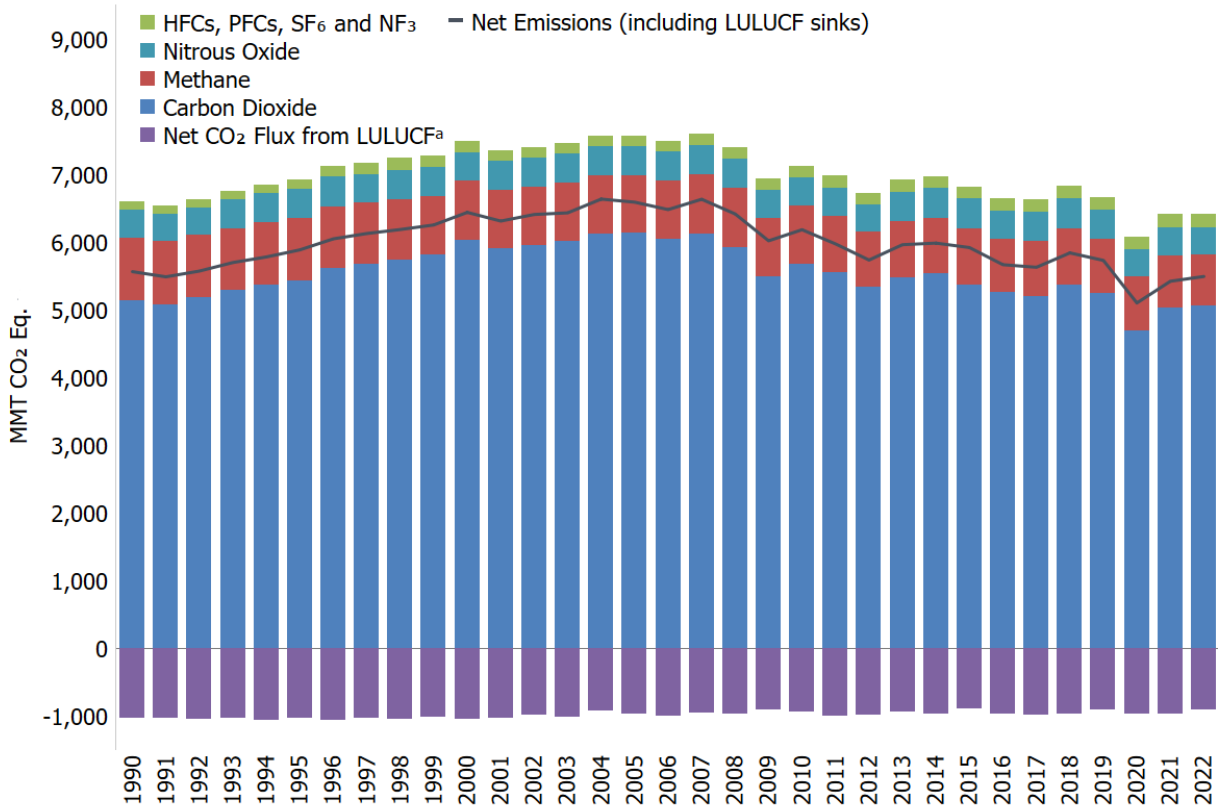
2.1 Overview of U.S. Greenhouse Gas Emissions and Sinks Trends

In 2022, total gross U.S. greenhouse gas emissions were 6,343.2 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).[1] Total gross U.S. emissions decreased by 3.0 percent from 1990 to 2022, down from a high of 15.2 percent above 1990 levels in 2007. Gross emissions increased from 2021 to 2022 by 0.2 percent (14.4 MMT CO_2 Eq.). Net emissions (i.e., including sinks) were 5,489.0 MMT CO_2 Eq. in 2022. Overall, net emissions increased by 1.3 percent from 2021 to 2022 and decreased by 16.7 percent from 2005 levels, as shown in Table 2-1. Between 2021 and 2022, the increase in total greenhouse gas emissions was driven largely by an increase in CO_2 emissions from fossil fuel combustion across most end-use sectors due in part to increased energy use from the continued rebound of economic activity after the height of the COVID-19 pandemic. The CO_2 emissions from fossil fuel combustion increased by 1.0 percent from 2021 to 2022, including a 5.0 percent increase in residential sector emissions, 8.9 percent increase in commercial sector emissions, 0.1 percent decrease in transportation sector emissions, 2.6 percent increase in industrial emissions, and 0.6 percent decrease in electric power sector emissions. Carbon sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector offset 14.5 percent of total emissions in 2022.

Figure 2-1 and Figure 2-2 illustrate the overall trend in total U.S. emissions and sinks since 1990, by gas and by annual percentage changes relative to the previous year.

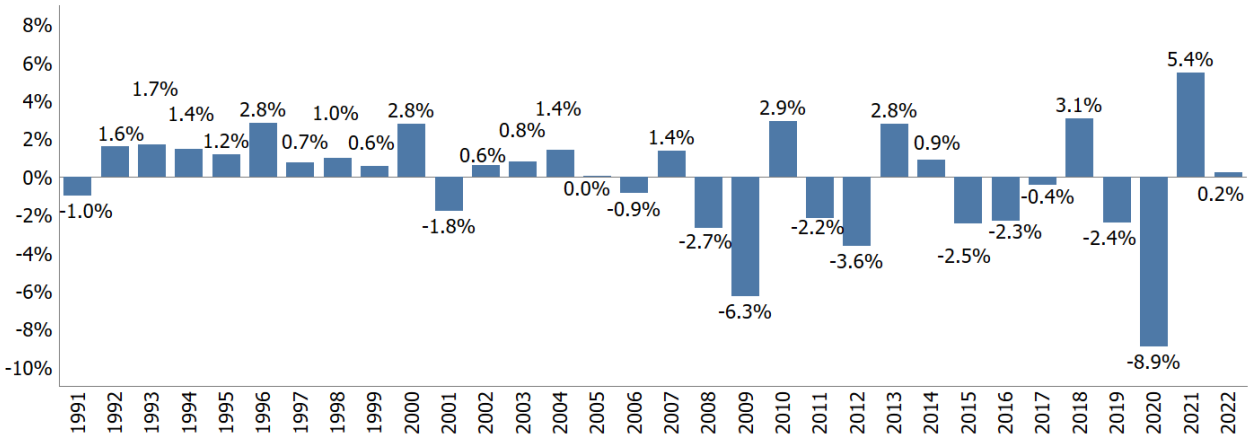
[1] The gross emissions total presented in this report for the United States excludes emissions and sinks from removals from LULUCF. The net emissions total presented in this report for the United States includes emissions and sinks from removals from LULUCF.

Figure 2-1: U.S. Greenhouse Gas Emissions and Sinks by Gas



[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

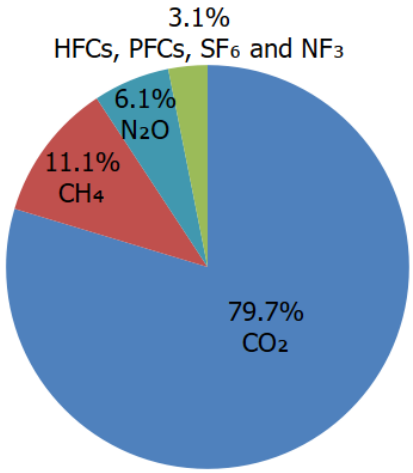
Figure 2-2: Annual Percentage Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year



Emissions and Sinks by Gas

Figure 2-3 illustrates the relative contribution of each gas to total gross U.S. greenhouse gas emissions in 2022, in CO_2 equivalents (i.e., weighted by global warming potential). The primary greenhouse gas emitted by human activities in the United States is CO_2, representing 79.7 percent of total greenhouse gas emissions. The largest source of CO_2—and of overall greenhouse gas emissions—is fossil fuel combustion, primarily from transportation and power generation. Methane (CH_4) emissions account for 11.1 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of waste in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management are the major sources of N_2O emissions. Ozone depleting substance (ODS) substitute emissions were the primary contributor to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions were attributable primarily to fluorochemical production and electronics manufacturing. Electrical equipment accounted for most sulfur hexafluoride (SF_6) emissions. Nitrogen trifluoride (NF_3) emissions were approximately evenly split between electronics manufacturing and fluorochemical production.

Figure 2-3: 2022 Gross Total U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)



Note: Emissions and removals from LULUCF are excluded from the figure above.

From 1990 to 2022, total emissions of CO_2 decreased by 1.5 percent (78.6 MMT CO_2 Eq.), total emissions of methane (CH_4) decreased by 19.4 percent (169.3 MMT CO_2 Eq.), and total emissions of nitrous oxide (N_2O) decreased by 4.5 percent (18.4 MMT CO_2 Eq.). During the same period, emissions of fluorinated gases including HFCs, PFCs, SF_6, and NF_3 rose by 57.9 percent (72.7 MMT CO_2 Eq.). Rapidly growing emissions of HFCs drove this trend, overwhelming decreases in emissions of PFCs and SF_6. Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6, and NF_3 are significant because many of them have extremely high global warming potentials (GWPs), and, in the cases of PFCs, SF_6, and NF_3, very long atmospheric lifetimes. U.S. greenhouse gas emissions were partly offset by carbon sequestration in managed forests, trees in urban areas, agricultural soils, landfilled yard trimmings, and coastal wetlands. These were estimated to offset 14.5 percent (921.8 MMT CO_2 Eq.) of total gross emissions in 2022.

Table 2-1 provides information on trends in emissions and sinks from all U.S. anthropogenic sources and sinks in weighted units of MMT CO_2 Eq., while unweighted gas emissions and sinks in kilotons (kt) are provided in Table 2-2.

Table 2-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Gas (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**5,131.6**	**6,126.9**	**5,362.2**	**5,234.5**	**4,689.0**	**5,017.2**	**5,053.0**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*
Electric Power Sector	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
Biomass and Biodiesel Consumption[a]	*237.9*	*245.4*	*336.0*	*333.1*	*295.7*	*303.0*	*305.4*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
CH_4[c]	**871.7**	**795.4**	**771.5**	**754.3**	**735.3**	**720.5**	**702.4**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+

Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O[c]	**408.2**	**419.2**	**439.5**	**416.4**	**391.2**	**398.2**	**389.7**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas Systems	+	+	+	+	+	+	0.2
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**
Substitution of Ozone Depleting Substances	0.3	99.5	157.9	162.1	166.2	172.6	178.1
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	+	+
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
Electrical Equipment	0.0	+	0.0	+	+	+	+
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8
SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**
LULUCF Emissions[c]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1
LULUCF Carbon Stock Change[e]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Sector Net Total[f]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

[e] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total (gross) emissions are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Table 2-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Gas (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**5,131,650**	**6,126,864**	**5,362,191**	**5,234,488**	**4,688,969**	**5,017,202**	**5,053,019**
Fossil Fuel Combustion	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
Transportation	*1,468,944*	*1,858,552*	*1,813,135*	*1,816,636*	*1,572,820*	*1,753,546*	*1,751,286*
Electric Power Sector	*1,819,951*	*2,400,057*	*1,753,432*	*1,606,721*	*1,439,566*	*1,540,933*	*1,531,680*
Industrial	*876,468*	*847,640*	*810,472*	*809,807*	*761,986*	*780,453*	*801,064*
Residential	*338,568*	*358,898*	*338,940*	*342,905*	*314,795*	*318,034*	*334,065*
Commercial	*228,293*	*227,130*	*246,297*	*251,749*	*229,264*	*237,528*	*258,733*
U.S. Territories	*20,010*	*51,857*	*25,923*	*24,813*	*23,279*	*23,772*	*22,575*
Non-Energy Use of Fuels	99,104	124,988	118,382	106,474	97,757	111,624	102,808
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884
Iron and Steel Production & Metallurgical Coke Production	104,740	70,082	42,863	43,095	37,724	41,873	40,672
Natural Gas Systems	32,427	26,312	32,768	38,525	36,719	35,780	36,470
Petrochemical Production	20,075	26,882	27,200	28,483	27,926	30,656	28,788
Petroleum Systems	9,585	10,210	34,777	45,498	28,937	24,140	21,967
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610
Incineration of Waste	12,900	13,254	13,339	12,948	12,921	12,476	12,357
Lime Production	11,700	14,552	13,106	12,112	11,299	11,870	12,208
Other Process Uses of Carbonates	7,103	8,472	7,938	8,973	9,012	8,583	10,384
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	6,113	6,150	5,805	6,600	7,053
Urea Fertilization	2,417	3,504	4,936	5,034	5,132	5,229	5,327
Carbon Dioxide Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000
Liming	4,690	4,351	2,240	2,203	2,887	2,387	3,268
Coal Mining	4,606	4,169	3,139	2,992	2,197	2,455	2,474
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704
Titanium Dioxide Production	1,195	1,755	1,541	1,340	1,340	1,474	1,474
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446
Ferroalloy Production	2,152	1,392	2,063	1,598	1,377	1,567	1,327
Zinc Production	632	1,030	999	1,026	977	1,007	947
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Lead Production	516	553	527	531	450	439	428
Carbide Production and Consumption	243	213	184	175	154	172	210
Abandoned Oil and Gas Wells	7	7	8	8	8	8	8
Substitution of Ozone Depleting Substances	+	1	3	3	4	4	4
Magnesium Production and Processing	129	4	2	2	3	3	3
Biomass and Biodiesel Consumption[a]	*237,946*	*245,421*	*335,971*	*333,057*	*295,695*	*303,014*	*305,417*
International Bunker Fuels[b]	*103,634*	*113,328*	*124,279*	*113,632*	*69,638*	*80,180*	*98,241*
CH_4[c]	**31,131**	**28,408**	**27,553**	**26,941**	**26,262**	**25,731**	**25,084**
Enteric Fermentation	6,539	6,722	7,028	7,045	7,010	7,017	6,878
Natural Gas Systems	7,813	7,505	6,795	6,741	6,439	6,235	6,183
Landfills	7,063	5,275	4,512	4,595	4,431	4,359	4,277
Manure Management	1,398	1,964	2,418	2,382	2,390	2,373	2,312
Coal Mining	3,860	2,552	2,110	1,892	1,648	1,595	1,558
Petroleum Systems	1,765	1,723	2,108	1,865	1,904	1,737	1,415
Wastewater Treatment	811	809	763	755	748	738	743
Rice Cultivation	677	735	711	558	664	653	674
Stationary Combustion	345	313	344	351	285	286	307
Abandoned Oil and Gas Wells	279	294	301	302	303	306	303
Abandoned Underground Coal Mines	288	264	247	237	232	224	225
Mobile Combustion	258	154	101	102	91	92	93
Composting	15	75	90	91	92	92	92
Field Burning of Agricultural Residues	19	23	22	23	22	22	22
Anaerobic Digestion at Biogas Facilities	+	+	+	1	+	+	+
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*3*	*3*	*3*
N_2O[c]	**1,540**	**1,582**	**1,658**	**1,571**	**1,476**	**1,503**	**1,471**
Agricultural Soil Management	1,090	1,110	1,258	1,191	1,102	1,124	1,097
Stationary Combustion	84	115	95	84	78	83	93
Wastewater Treatment	56	68	80	81	84	83	83
Manure Management	50	57	63	63	64	65	64
Mobile Combustion	145	140	67	72	61	63	63
Nitric Acid Production	41	38	32	34	31	30	33
N_2O from Product Uses	14	14	14	14	14	14	14
Adipic Acid Production	51	24	35	18	28	25	8
Composting	1	6	7	7	7	7	7
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	5	5	4	5	5
Incineration of Waste	2	1	1	1	1	1	1
Electronics Industry	+	+	1	1	1	1	1

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Field Burning of Agricultural Residues	1	1	1	1	1	1	1
Natural Gas Systems	+	+	+	+	+	+	1
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*4*	*3*	*2*	*2*	*3*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	M	M	M	M	M	M	M
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
SF_6 and PFCs from Other Product Use	101	83	178	173	167	138	172
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Electrical Equipment	+	+	0	+	+	+	+
SF_6	**2**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	1	1	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
SF_6 and PFCs from Other Product Use	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.
M (Mixture of multiple gases)
NO (Not Occurring)
[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.
[b] Emissions from international bunker fuels are not included in totals.
[c] LULUCF emissions of LULUCF CH_4 and N_2O are reported separately from gross emissions totals. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.
[d] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.
Notes: Totals by gas may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Emissions and Sinks by UNFCCC/IPCC Sector

Emissions and removals of all gases can be summed from each source and sink category into a set of five sectors defined by the Paris Agreement and UNFCCC reporting guidelines and methodological framework provided by the Intergovernmental Panel on Climate Change (IPCC). Figure 2-4 and Table 2-3 illustrate that over the 33-year period of 1990 to 2022, total emissions from the Energy and Waste sectors decreased by 3.4 percent (181.2 MMT CO_2 Eq.) and 29.3 percent (69.1 MMT CO_2 Eq.), respectively. Emissions from Industrial Processes and Product Use and Agriculture grew by 3.9 percent (14.4 MMT CO_2 Eq.) and 7.7 percent (42.2 MMT CO_2 Eq.), respectively. Over the same period, total carbon sequestration in the LULUCF sector decreased by 12.5 percent (122.5 MMT CO_2), and emissions from the LULUCF sector increased by 16.5 percent (9.6 MMT CO_2 Eq.).

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by IPCC Sector

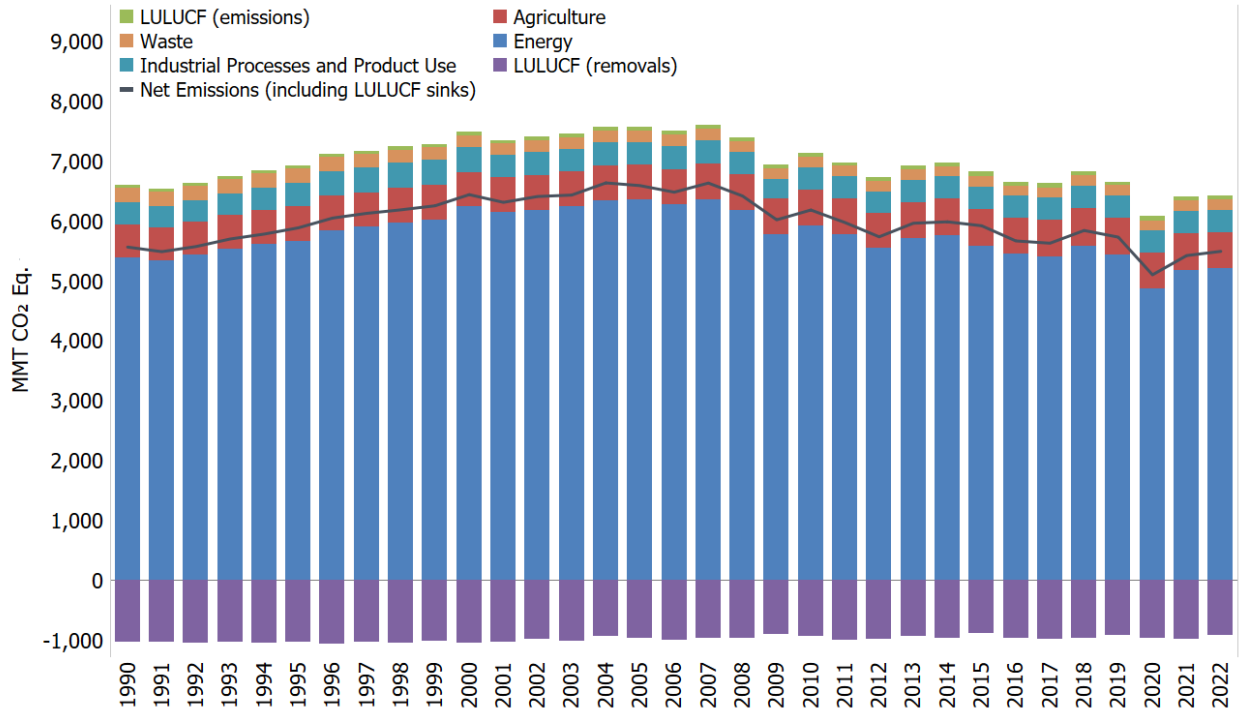


Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by UNFCCC/IPCC Sector/Category (MMT CO_2 Eq.)

UNFCCC/IPCC Sector/Category	1990	2005	2018	2019	2020	2021	2022
Energy	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Natural Gas Systems	251.2	236.5	223.0	227.3	217.0	210.4	209.7
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Petroleum Systems	59.0	58.5	93.8	97.8	82.3	72.8	61.6
Coal Mining	112.7	75.6	62.2	56.0	48.3	47.1	46.1
Stationary Combustion[a]	32.0	39.3	34.7	32.0	28.5	30.1	33.3
Mobile Combustion	45.6	41.3	20.5	21.9	18.7	19.4	19.3
Incineration of Waste	13.3	13.6	13.7	13.3	13.3	12.8	12.7
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Biomass and Biodiesel Consumption[b]	*237.9*	*245.4*	*336.0*	*333.1*	*295.7*	*303.0*	*305.4*
International Bunker Fuels[c]	*104.6*	*114.3*	*125.3*	*114.6*	*70.3*	*80.9*	*99.1*
Industrial Processes and Product Use	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**
Substitution of Ozone Depleting Substances	0.3	99.5	157.9	162.1	166.2	172.7	178.1
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.8	70.1	42.9	43.1	37.7	41.9	40.7
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
Fluorochemical Production	70.9	30.0	8.7	9.3	6.9	7.1	7.8

Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Electrical Equipment	24.7	11.9	5.0	6.1	5.9	6.0	5.1
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Electronics Industry	3.3	4.5	4.8	4.5	4.5	4.8	4.7
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Aluminum Production	26.1	7.2	2.9	3.3	3.2	2.5	2.2
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Magnesium Production and Processing	5.7	3.0	1.1	1.0	0.9	1.2	1.2
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
SF_6 and PFCs from Other Product Use	1.4	1.5	0.9	0.8	0.7	0.5	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Manure Management	52.5	70.2	84.3	83.5	83.8	83.6	81.7
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.9	0.8	0.8	0.8
Waste	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Wastewater Treatment	37.5	40.7	42.5	42.7	43.2	42.7	42.7
Composting	0.7	3.6	4.3	4.3	4.4	4.4	4.4
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+
Total Gross Emissions[d] (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**
LULUCF Sector Net Total[e]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**
Forest Land	(1,069.0)	(960.2)	(963.8)	(907.3)	(946.6)	(924.2)	(872.0)
Cropland	40.4	2.9	14.2	12.0	20.5	2.9	3.4
Grassland	59.8	46.7	54.9	54.3	45.8	36.0	39.6
Wetlands	44.0	41.2	38.9	38.9	38.8	38.8	38.8
Settlements	(51.9)	(38.1)	(59.7)	(61.4)	(63.0)	(64.1)	(64.1)
Net Emission (Sources and Sinks)[f]	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes CH_4 and N_2O emissions from fuel combustion.

[b] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[c] Emissions from international bunker fuels are not included in totals.

[d] Total emissions without LULUCF.

[e] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] Net emissions with LULUCF.

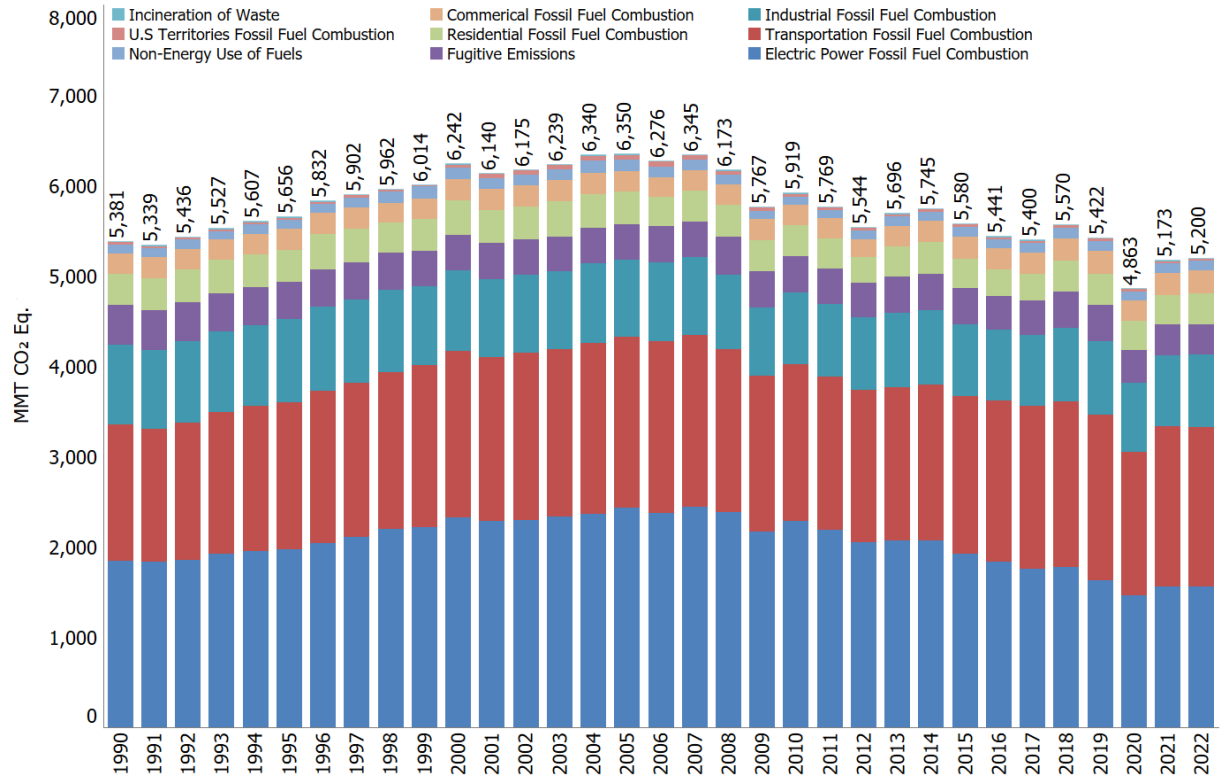
Notes: Total (gross) emissions are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

Emissions from energy-related activities come from two main categories: 1) direct emissions associated with fuel use (i.e., fossil fuel combustion, non-energy use of fossil fuels and waste combustion), and 2) fugitive emissions mainly from coal, natural gas, and oil production. Energy emissions also include some categories that are not added to Energy sector totals but are instead presented as memo items, including international bunker fuels and biomass emissions. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions from 1990 through 2022. Fossil fuel combustion is the largest source of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-5). Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered in detail in the Energy chapter (see Chapter 3).

In 2022, 83.0 percent of the energy used in the United States on a Btu basis was produced through the combustion of fossil fuels. The remaining 17.0 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy. A discussion of specific trends related to CO_2 and other greenhouse gas emissions from energy use is presented here with more detail in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.2 percent and 10.8 percent of gross total U.S. emissions of each gas, respectively).[2] Table 2-4 presents greenhouse gas emissions from the Energy chapter by source and gas.

Figure 2-5: Trends in Energy Sector Greenhouse Gas Sources



[2] The contribution of energy non-CO_2 emissions is based on gross totals so excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related CH_4 and N_2O including LULUCF non-CO_2 emissions, is 37.1 percent and 9.8 percent, respectively.

Table 2-4: Emissions from Energy by Gas (MMT CO_2 Eq.)[3]

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**4,910.9**	**5,923.1**	**5,190.6**	**5,059.1**	**4,520.2**	**4,840.7**	**4,875.5**	**-0.7%**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4	-1.1%
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*	*19.2%*
Electricity Generation	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*	*-15.8%*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*	*-8.6%*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*	*-1.3%*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*	*13.3%*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*	*12.8%*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8	3.7%
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5	12.5%
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0	129.2%
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4	-4.2%
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5	-46.3%
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+	13.0%
Biomass-Wood[a]	*215.2*	*206.9*	*220.0*	*217.7*	*190.6*	*192.5*	*195.3*	*-9.2%*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*	*-5.2%*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*81.9*	*82.6*	*71.8*	*79.1*	*79.6*	*1783.2%*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*	*100.0%*
Biomass-MSW[a]	*18.5*	*14.7*	*16.1*	*15.7*	*15.6*	*15.3*	*14.9*	*-19.8%*
CH_4	**409.0**	**358.5**	**336.2**	**321.7**	**305.3**	**293.3**	**282.4**	**-31.0%**
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1	-20.9%
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6	-59.6%
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6	-19.8%
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6	-10.8%
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5	8.8%
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3	-21.8%
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6	-63.8%
Incineration of Waste	+	+	+	+	+	+	+	-17.9%
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*-51.8%*
N_2O	**61.2**	**67.9**	**43.2**	**41.6**	**37.1**	**39.2**	**41.9**	**-31.5%**
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7	10.6%
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7	-56.5%
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3	-17.9%
Natural Gas Systems	+	+	+	+	+	+	0.2	3,204.7%
Petroleum Systems	+	+	+	+	+	+	+	282.0%
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*	*1.4%*
Total	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**	**-3.4%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from biomass and biofuel consumption are not included specifically in Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines*, the Paris Agreement and the UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

[3] The full time series data is available in Common Reporting Tables (CRTs) included in the U.S. Paris Agreement and UNFCCC submission and in CSV format available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Fossil Fuel Combustion CO_2 Emissions

As the largest contributor to U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 74.6 percent of CO_2-equivalent total gross emissions on average across the time series. Within the United States, fossil fuel combustion accounted for 93.0 percent of CO_2 emissions in 2022. Emissions from this source category include CO_2 associated with the combustion of fossil fuels (coal, natural gas, and petroleum) for energy use. Fossil fuel combustion CO_2 emissions decreased by 1.1 percent (52.8 MMT CO_2 Eq.) from 1990 to 2022 and were responsible for most of the decrease in national emissions during this period. Similarly, CO_2 emissions from fossil fuel combustion have decreased by 18.2 percent (1,044.7 MMT CO_2 Eq.) since 2005. From 2021 to 2022, these emissions increased by 1.0 percent (45.1 MMT CO_2 Eq.).

Historically, changes in emissions from fossil fuel combustion have been the main factor influencing U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion since 1990 are affected by many long-term and short-term factors, including population and economic growth, energy price fluctuations and market trends, technological changes, carbon intensity of energy fuel choices, and seasonal temperatures. On an annual basis, the overall consumption and mix of fossil fuels in the United States fluctuates in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. For example, coal consumption for electric power is influenced by factors such as the relative price of coal and alternative sources, the ability to switch fuels, and longer-term trends in coal markets. Fossil fuel combustion CO_2 emissions also depend on the type of fuel consumed or energy used and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, reduces CO_2 emissions because of the lower carbon content of natural gas (see Table 3-12 in Chapter 3 for more detail on electricity generation by source and see Table A-19 in Annex 2.1 for more detail on the carbon content coefficient of different fossil fuels).

Overall CO_2 emissions from electric power generation decreased by 36.2 percent from 2005 to 2022 (see Figure 2-7), reflecting the continued shift in the share of electric power generation from coal to natural gas and renewables since 2005. Carbon dioxide emissions from coal combustion for electric power generation gradually increased between 1990 and 2007, then began to decrease at a faster rate from 2008 to 2022. Carbon dioxide emissions from natural gas combustion for electric power generation remained relatively constant, with a slight increase between 1990 and 2009, then began to consistently increase between 2010 and 2022.

Petroleum use is another major driver of CO_2 emissions from fossil fuel combustion, particularly in the transportation sector, which has represented the largest source of CO_2 emissions from fossil fuel combustion since 2017. Emissions from petroleum consumption for transportation (including bunker fuels) decreased by 0.1 percent from 2021 to 2022. Fuel economy of light-duty vehicles is an important factor in transportation sector CO_2 emissions trends. The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period and has slowed the rate of increase of CO_2 emissions.

Trends in CO_2 emissions from fossil fuel combustion by end-use sector are presented in Table 2-5 and Figure 2-6 based on the underlying U.S. energy consumer data collected by the U.S. Energy Information Administration (EIA). Figure 2-7 further describes trends in direct and indirect CO_2 emissions from fossil fuel combustion by end-use sector. Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA "end-use sectors" based on total fuel consumption and appropriate fuel properties described below.[4]

- *Transportation.* EIA's fuel consumption data for the transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another.
- *Electric Power.* EIA's fuel consumption data for the electric power sector are composed of electricity-only and combined-heat-and-power (CHP) plants within the North American Industry Classification System (NAICS) 22 category whose primary business is to sell electricity, or electricity and heat, to the public.

[4] Additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report.

(Non-utility power producers are included in this sector as long as they meet the electric power sector definition.)

- *Industry.* EIA statistics for the industrial sector include fossil fuel consumption that occurs in the fields of manufacturing, agriculture, mining, and construction. EIA's fuel consumption data for the industrial sector consist of all facilities and equipment used for producing, processing, or assembling goods. (EIA includes generators that produce electricity and/or useful thermal output primarily to support on-site industrial activities in this sector.)
- *Residential.* EIA's fuel consumption data for the residential sector consist of living quarters for private households.
- *Commercial.* EIA's fuel consumption data for the commercial sector consist of service-providing facilities and equipment from private and public organizations and businesses. (EIA includes generators that produce electricity and/or useful thermal output primarily to support the activities at commercial establishments in this sector.)

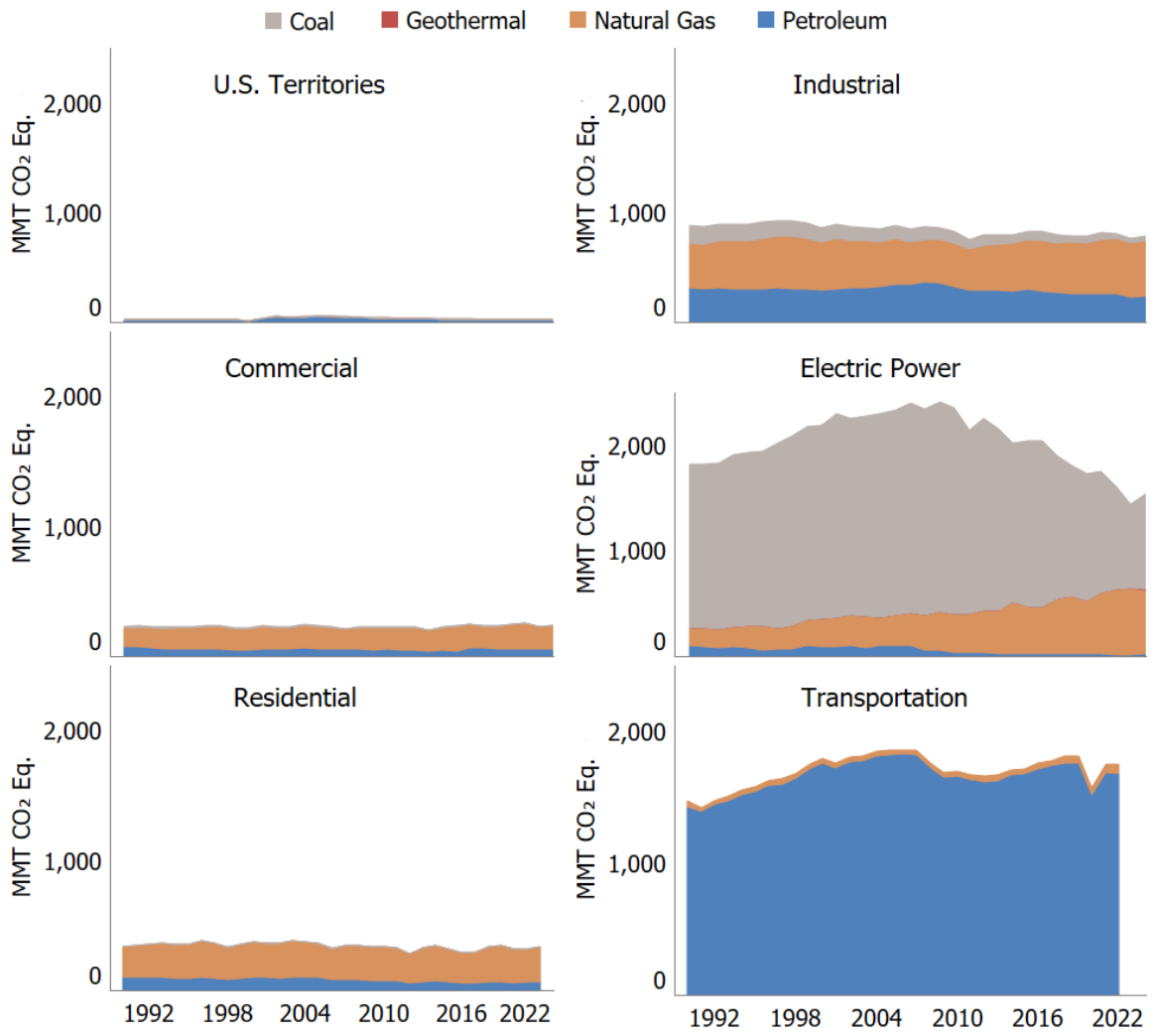
Table 2-5: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,472.0**	**1,863.3**	**1,817.9**	**1,821.4**	**1,576.9**	**1,758.6**	**1,757.4**
Combustion	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3
Electricity	3.0	4.7	4.8	4.8	4.1	5.0	6.1
Industrial	**1,562.9**	**1,584.0**	**1,311.8**	**1,275.3**	**1,171.8**	**1,225.6**	**1,238.0**
Combustion	876.5	847.6	810.5	809.8	762.0	780.5	801.1
Electricity	686.4	736.3	501.3	465.5	409.8	445.1	437.0
Residential	**931.3**	**1,214.9**	**981.2**	**926.7**	**860.1**	**890.3**	**899.4**
Combustion	338.6	358.9	338.9	342.9	314.8	318.0	334.1
Electricity	592.7	856.0	642.3	583.7	545.3	572.2	565.3
Commercial	**766.0**	**1,030.1**	**851.3**	**804.4**	**709.6**	**756.1**	**782.0**
Combustion	228.3	227.1	246.3	251.7	229.3	237.5	258.7
Electricity	537.7	803.0	605.0	552.7	480.3	518.5	523.3
U.S. Territories[a]	**20.0**	**51.9**	**25.9**	**24.8**	**23.3**	**23.8**	**22.6**
Total	**4,752.2**	**5,744.1**	**4,988.2**	**4,852.6**	**4,341.7**	**4,654.3**	**4,699.4**
Electric Power	**1,820.0**	**2,400.1**	**1,753.4**	**1,606.7**	**1,439.6**	**1,540.9**	**1,531.7**

[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) is included in this report.

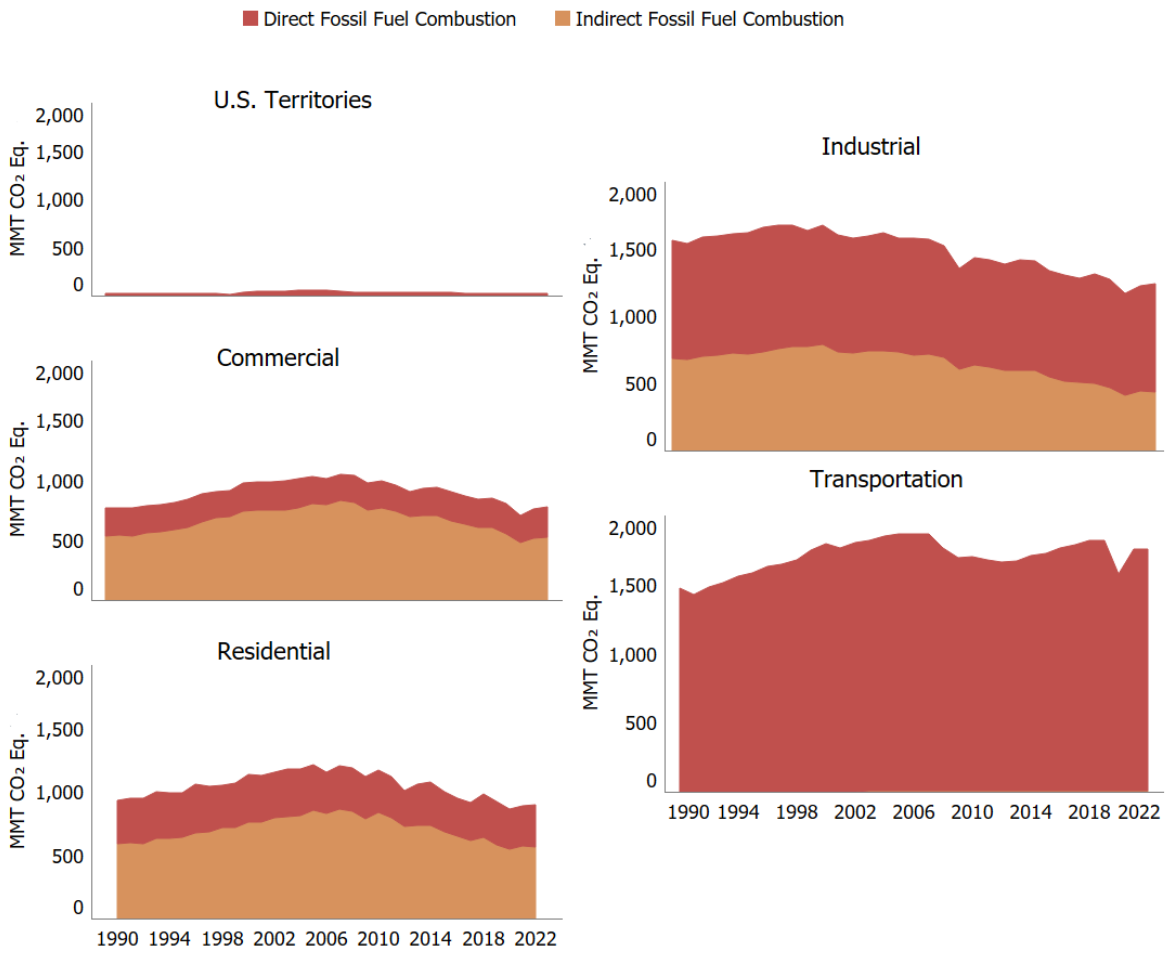
Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector. Totals may not sum due to independent rounding.

Figure 2-6: Trends in CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector and Fuel Type



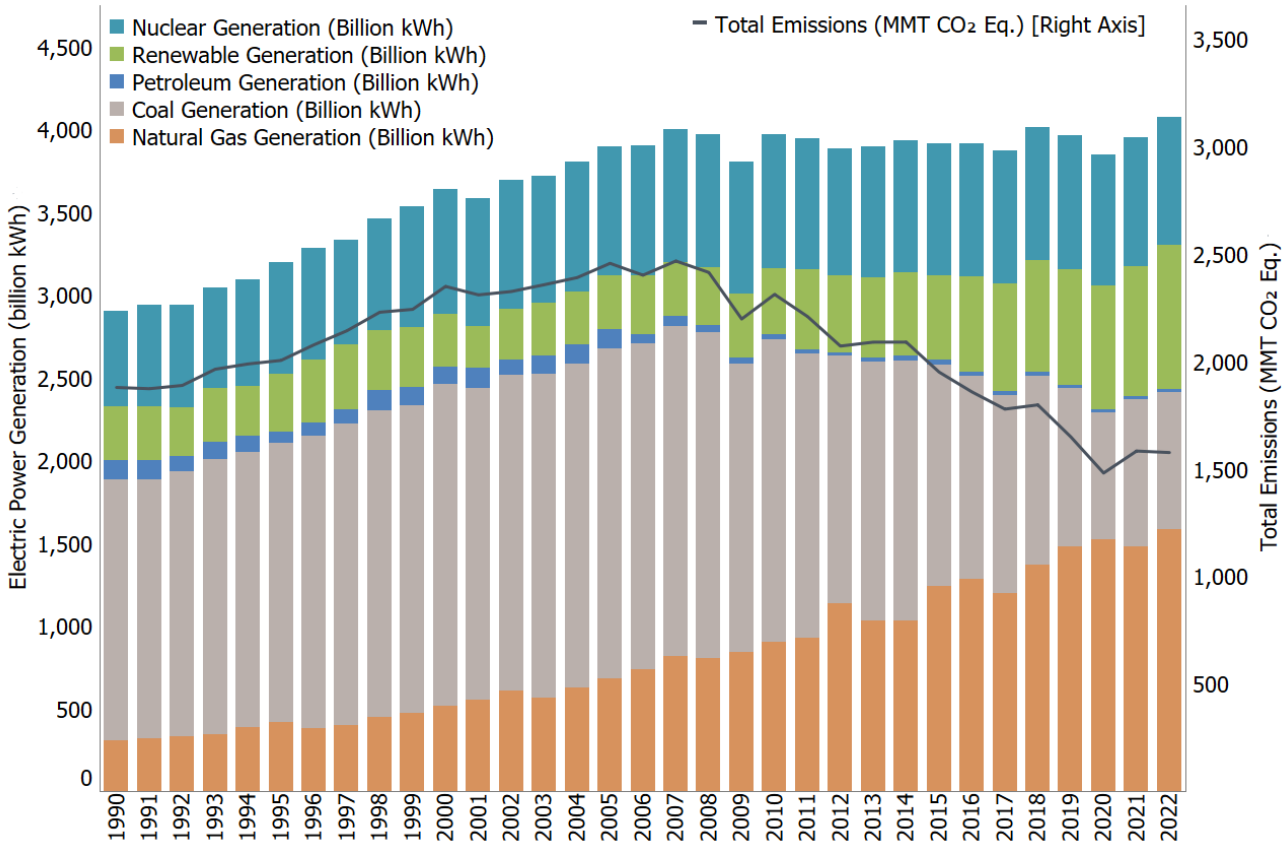
Note: Fossil fuel combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation. Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Figure 2-7: Trends in End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Electric power was the second largest end-use emitter of CO_2 in 2022 (surpassed by transportation in 2017); electric power generators used 30.5 percent of U.S. energy from fossil fuels and emitted 32.6 percent of the CO_2 from fossil fuel combustion in 2022. CO_2 emissions from the fossil fuel combustion in the electric power sector decreased by 0.6 percent between 2021 and 2022 due to changes in the mix of electric generation resources. Between 2021 and 2022 overall electricity generation increased by 3 percent, coal electricity generation decreased by 10.2 percent, natural gas generation increased by 4.0 percent, and renewable energy generation increased by 7.6 percent. Changes in electricity demand and the carbon intensity of fuels used for electric power generation have a significant impact on CO_2 emissions. Carbon dioxide emissions from fossil fuel combustion from the electric power sector have decreased by 15.8 percent since 1990, and the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, has decreased by 27.6 percent during that same timeframe. This decoupling of electric power generation and the resulting CO_2 emissions is shown below in Figure 2-8.

Figure 2-8: Electric Power Generation (Billion kWh) and Emissions (MMT CO_2 Eq.)



Electric power CO_2 emissions can also be allocated to the end-use sectors that use electricity, as presented in Table 2-5. With electricity CO_2 emissions allocated to end-use sectors, the transportation end-use sector represents the largest source of fossil fuel combustion emissions accounting for 1,757.4 MMT CO_2 Eq. in 2022 or 37.4 percent of total CO_2 emissions from fossil fuel combustion, a 0.1 percent decrease since 2021. The industrial end-use sector accounted for 26.3 percent of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions, an increase of 1.0 percent since 2021. From 2021 to 2022, total energy use in the industrial sector increased by 1.8 percent due to an increase in total industrial production and manufacturing output. The residential and commercial end-use sectors accounted for 19.1 and 16.6 percent, respectively, of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions. Both of these end-use sectors were heavily reliant on electricity for meeting building-related energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances contributing 62.9 and 66.9 percent of emissions from the residential and commercial end-use sectors, respectively. From 2021 to 2022, an increase in heating degree days (7.9 percent) increased energy demand for heating in the residential and commercial sectors; also, a 4.3 percent increase in cooling degree days compared to 2021 increased demand for air conditioning in the residential and commercial sectors. As a result, CO_2 emissions from the residential and commercial end-use sectors when including allocated electricity emissions increased by 1.0 and 3.4 percent since 2021, respectively.

Other Energy Sector Trends

Energy sector emissions increased by 0.5 percent since 2021 and decreased by 3.4 percent since 1990. Other notable trends in emissions from energy source categories (Figure 2-6 and Figure 2-7) over the 33-year period from 1990 through 2022 included the following:

- Emissions (CH_4, CO_2, and N_2O) from oil and gas systems decreased by 13.0 percent (38.8 MMT CO_2 Eq.) since 1990 and decreased by 4.2 percent (11.8 MMT CO_2 Eq.) from 2021 to 2022. Natural gas systems CH_4 emissions have decreased by 20.9 percent (45.7 MMT CO_2 Eq.) since 1990, due to a decrease in emissions from the distribution, transmission and storage, processing, and exploration segments. The decrease in distribution emissions is due mainly to reduced emissions from pipeline and distribution station leaks, and the decrease in transmission and storage emissions is due mainly to reduced compressor station emissions (including emissions from compressors and leaks). Over the same time period (i.e., since 1990), methane emissions from the natural gas production segment increased due to increased gathering and boosting emissions. Between 2021 and 2022, methane emissions from natural gas systems decreased 0.8 percent, due to a decrease in emissions from production segment pneumatic controllers. Petroleum systems CH_4 emissions decreased by 19.8 percent (9.8 MMT CO_2 Eq.) since 1990 and 18.5 percent between 2021 and 2022. This decrease is due primarily to decreases in emissions from offshore platforms, tanks, and pneumatic controllers. Carbon dioxide emissions from natural gas and petroleum systems increased by 39.1 percent (16.4 MMT CO_2) from 1990 to 2022 and decreased by 2.5 percent between 2021 and 2022. This increase since 1990 is due primarily to increases in the production segment, where emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time. The decrease in emissions between 2021 and 2022 and is also due primarily to the production segment, where flaring emissions decreased for associated gas and tanks.
- Methane emissions from coal mining decreased by 59.6 percent (64.4 MMT CO_2 Eq.) from 1990 through 2022 and by 2.3 percent between 2021 and 2022 primarily due to a decrease in the number of active mines and annual coal production over the 1990 to 2022 time period. Between 2021 and 2022, the number of mines and coal production increased.
- Nitrous oxide emissions from mobile combustion decreased by 56.5 percent (21.7 MMT CO_2 Eq.) from 1990 through 2022 and by 0.7 percent (0.1 MMT CO_2 Eq.) between 2021 and 2022, primarily as a result of national vehicle criteria pollutant emissions standards and emission control technologies for on-road vehicles.
- Nitrous oxide emissions from stationary combustion were the third largest source of anthropogenic N_2O emissions in 2022, accounting for 6.3 percent of N_2O emissions and 0.4 percent of total gross U.S. greenhouse gas emissions in 2022. Stationary combustion emissions peaked in 2007 and have steadily decreased since then.
- Carbon dioxide emissions from non-energy uses of fossil fuels increased by 3.7 percent (3.7 MMT CO_2 Eq.) from 1990 through 2022 but decreased by 7.9 percent (8.8 MMT CO_2 Eq.) between 2021 and 2022. Emissions from non-energy uses of fossil fuels were 102.8 MMT CO_2 Eq. in 2022, which constituted 2.0 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- Carbon dioxide emissions from incineration of waste decreased slightly by 4.2 percent (0.5 MMT CO_2 Eq.) from 1990 through 2022, as the volume of scrap tires and other fossil carbon-containing materials in waste decreased. Emissions decreased 0.9 percent (0.1 MMT CO_2 Eq.) between 2021 and 2022, consistent with trends across the time series.

Industrial Processes and Product Use

Greenhouse gases can be generated and emitted by industry in two different ways. First, they are generated and emitted as the byproducts of many non-energy-related industrial activities. For example, industrial processes can chemically or physically transform raw materials, which often release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). In the case of byproduct emissions, the emissions are generated by an industrial process itself, and are not directly a result of energy consumed during the process.

Second, industrial manufacturing processes and use by end-consumers also release HFCs, PFCs, SF_6, and NF_3 and other man-made compounds. In addition to the use of HFCs and some PFCs as substitutes for ozone depleting substances (ODS), fluorinated compounds such as HFCs, PFCs, SF_6, NF_3, and others are also emitted through use by

a number of other industrial sources in the United States. These industries include the electronics industry, electrical equipment, and magnesium metal production and processing. In addition, N_2O is used in and emitted by the electronics industry and anesthetic and aerosol applications, PFCs and SF_6 are emitted from other product use, and CO_2 is consumed and emitted through various end-use applications.

Emission sources in the Industrial Processes and Product Use (IPPU) chapter accounted for 6.0 percent of U.S. greenhouse gas emissions in 2022. Emissions from the IPPU sector increased by 3.9 percent from 1990 to 2022. The use of HFCs as substitutes for ODS is the largest source of emissions in this sector, contributing 46.5 percent of IPPU emissions in 2022 and driving growth since 1990. From 2021 to 2022, total emissions from IPPU increased 0.4 percent between 2021 and 2022. Despite the sectoral increase in emissions, emissions from adipic acid production decreased by almost 70 percent, emissions from ferroalloy production decreased by over 10 percent, and emissions from aluminum production, petrochemical production and zinc production decreased by between 5 and 10 percent. Figure 2-9 presents greenhouse gas emissions from IPPU by source category.

Figure 2-9: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

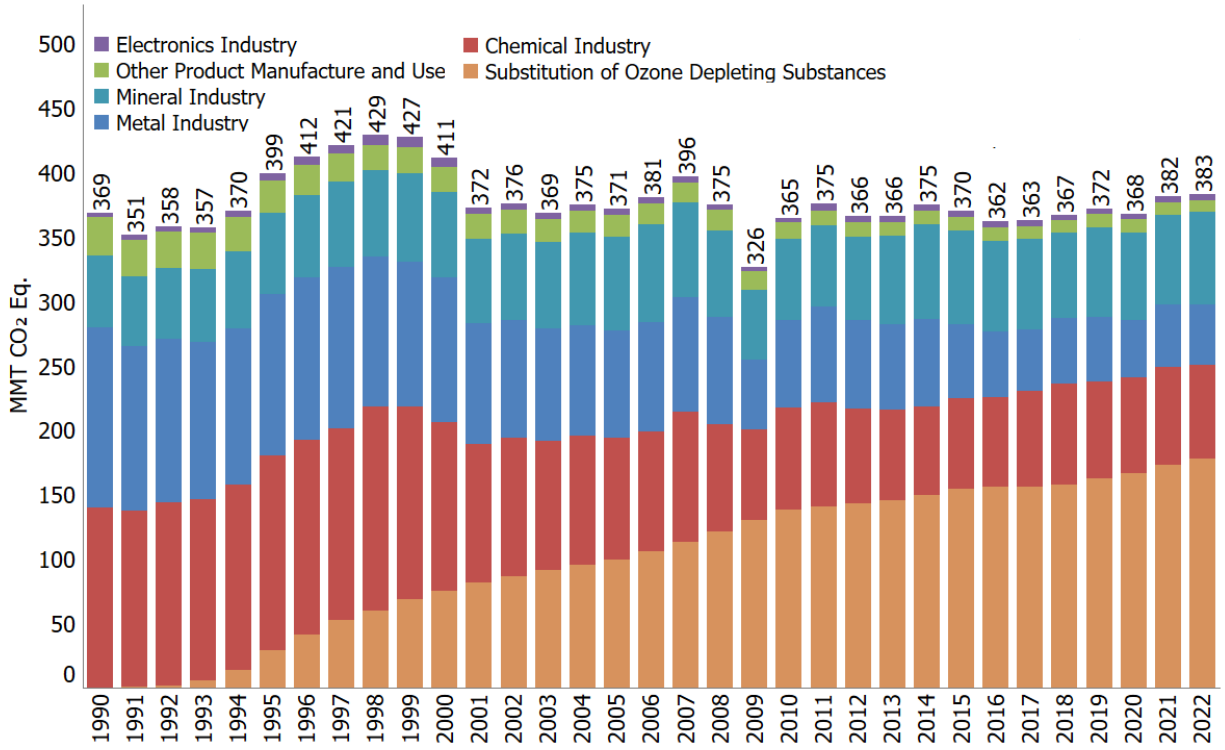


Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**213.7**	**195.9**	**164.4**	**168.2**	**160.7**	**168.8**	**168.9**	**-20.9%**
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9	25.1%
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7	-61.2%
Iron and Steel Production	*99.1*	*66.2*	*41.6*	*40.1*	*35.4*	*38.6*	*37.7*	*-62.0%*
Metallurgical Coke Production	*5.6*	*3.9*	*1.3*	*3.0*	*2.3*	*3.2*	*3.0*	*-47.3%*
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8	43.4%
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6	-12.5%

Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2	4.3%
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4	46.2%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1	86.4%
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0	239.7%
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0	-13.6%
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7	19.0%
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5	23.3%
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4	-78.8%
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3	-38.3%
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9	49.9%
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8	-45.0%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4	-17.1%
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2	-13.7%
Substitution of Ozone Depleting Substances[a]	+	+	+	+	+	+	+	28,664.2%
Magnesium Production and Processing	0.1	+	+	+	+	+	+	-97.7%
CH_4	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**	**-48.9%**
Carbide Production and Consumption	+	+	+	+	+	+	+	-38.5%
Ferroalloy Production	+	+	+	+	+	+	+	-45.2%
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+	-67.8%
Petrochemical Production	+	+	+	+	+	+	+	-21.7%
N_2O	**29.6**	**22.2**	**23.1**	**18.7**	**20.8**	**19.7**	**16.1**	**-45.7%**
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6	-20.2%
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8	-0.4%
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1	-84.5%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3	-10.5%
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3	720.0%
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**	**282.9%**
Substitution of Ozone Depleting Substances[a]	0.3	99.5	157.9	162.1	166.2	172.6	178.1	70,357.0%
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3	-90.9%
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3	74.0%
Magnesium Production and Processing	NO	NO	0.1	0.1	0.1	+	+	100.0%
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**	**-83.1%**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0	-83.1%
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7	7.8%
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8	-96.1%
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2	39.4%
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+	100.0%
Electrical Equipment	+	+	NO	+	+	+	+	-99.2%
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**	**-80.0%**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1	-79.4%
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1	-80.0%
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8	47.0%

SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6	-53.0%
Fluorochemical Production	5.8	3.3	+	+	+	+	+	-100.0%
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**	**238.3%**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6	1313.8%
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5	72.7%
Total	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**	**3.9%**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

Note: Totals may not sum due to independent rounding.

IPPU sector emissions increased 0.4 percent since 2021 and 3.9 percent since 1990. Some significant trends in U.S. emissions from IPPU source categories over the 33-year period from 1990 through 2022 included the following:

- HFC and PFC emissions resulting from the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) increased from small amounts in 1990 to 178.1 MMT CO_2 Eq. in 2022 (an increase of 70,357 percent).
- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production decreased by 2.9 percent from 2021 to 2022 to 40.7 MMT CO_2 Eq. and declined overall by 61.2 percent (64.1 MMT CO_2 Eq.) from 1990 through 2022, due to restructuring of the industry. The trend in the United States has been a shift toward fewer integrated steel mills and more electric arc furnaces (EAFs). EAFs use scrap steel as their main input and generally have lower on-site emissions.
- Carbon dioxide emissions from petrochemical production increased by 43.4 percent between 1990 and 2022, from 20.1 MMT CO_2 Eq. to 28.8 MMT CO_2 Eq. The increase in emissions is largely driven by the production of ethylene more than doubling over that period.
- Carbon dioxide emissions from ammonia production have decreased by 12.5 percent (1.8 MMT CO_2 Eq.) since 1990. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia from year to year. Emissions from ammonia production have increased since 2016, due to the addition of new ammonia production facilities and new production units at existing facilities. Agricultural demands continue to drive demand for nitrogen fertilizers and the need for new ammonia production capacity.
- Carbon dioxide emissions from cement production increased by 25.1 percent (8.4 MMT CO_2 Eq.) from 1990 through 2022. Emissions rose from 1990 through 2006 and then fell until 2009, due to a decrease in demand for construction materials during the economic recession. Since 2010, CO_2 emissions from cement production have risen by 33.2 percent.
- HFC, PFC, SF_6, and NF_3 emissions from fluorochemical production decreased by 89.0 percent (63.2 MMT CO_2 Eq.) from 1990 to 2022 due to a reduction in the HFC-23 emission rate from HCFC-22 production (kg HFC-23 emitted/kg HCFC-22 produced), the imposition of emissions controls at production facilities, and a decrease in SF_6 production due to the cessation of production at the major SF_6 production facility in 2010.
- PFC emissions from aluminum production decreased by 96.1 percent (18.5 MMT CO_2 Eq.) from 1990 to 2022, due to both industry emission reduction efforts and lower domestic aluminum production.
- SF_6 emissions from electrical equipment decreased by 79.4 percent (19.6 MMT CO_2 Eq.) from 1990 to 2022 due to a sharp increase in the price of SF_6 during the 1990s and industry emission reduction efforts.

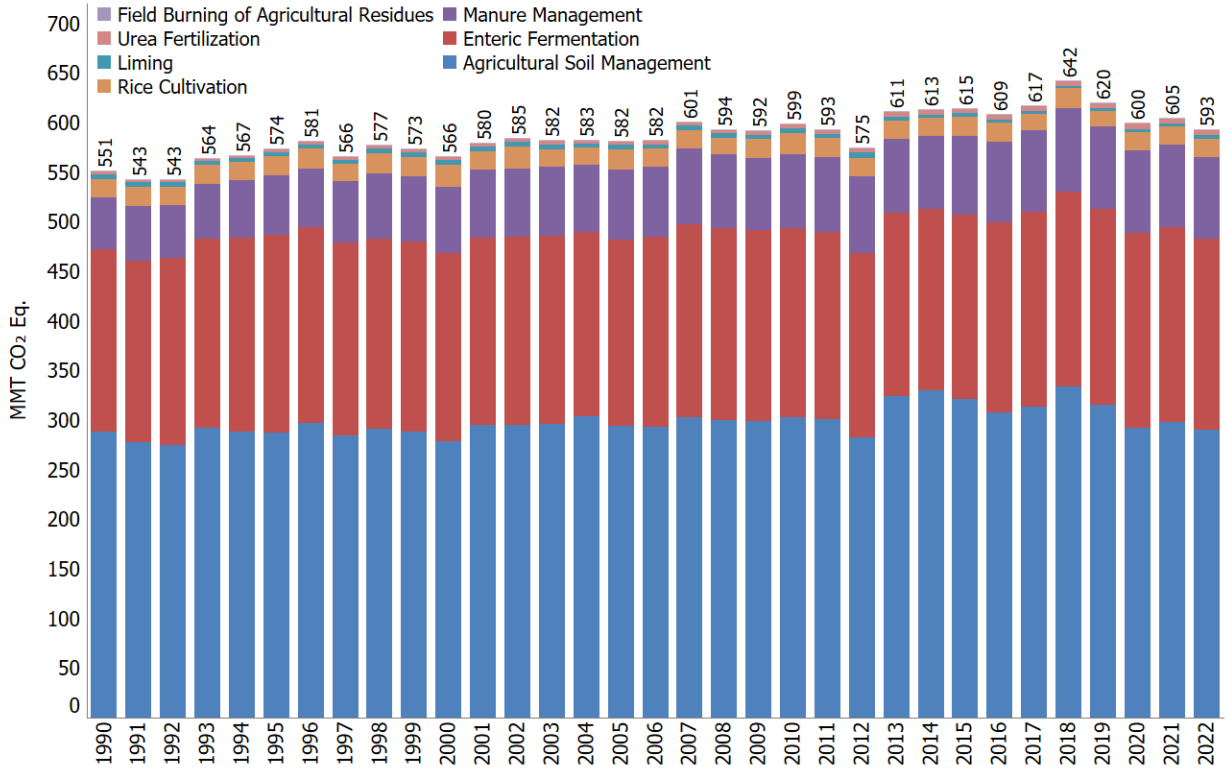
Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues. Methane and N_2O are the primary greenhouse gases emitted by agricultural activities, with

small amounts of CO_2 also emitted.[5] Carbon stock changes from agricultural soils are included in the LULUCF sector.

In 2022, agricultural activities were responsible for emissions of 593.4 MMT CO_2 Eq., or 9.4 percent of total U.S. greenhouse gas emissions. Agricultural soil management activities, such as the application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to agricultural-related emissions (49.0 percent) and were the largest source of U.S. N_2O emissions in 2022, accounting for 74.6 percent. Methane emissions from enteric fermentation and manure management represented 27.4 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2022. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities. Figure 2-10 and Table 2-7 illustrate agricultural greenhouse gas emissions by source and gas.

Figure 2-10: Trends in Agriculture Sector Greenhouse Gas Sources



[5] The contribution of agriculture non-CO_2 emissions is based on gross totals and excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of agriculture CH_4 and N_2O including LULUCF non-CO_2 emissions, is 40.5 percent and 48.3 percent, respectively.

Table 2-7: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CO_2	**7.1**	**7.9**	**7.2**	**7.2**	**8.0**	**7.6**	**8.6**	**21.0%**
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3	120.4%
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3	-30.3%
CH_4	**241.7**	**264.4**	**285.0**	**280.2**	**282.4**	**281.8**	**276.8**	**14.5%**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6	5.2%
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7	65.3%
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9	-0.4%
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6	14.4%
N_2O	**302.3**	**309.5**	**350.2**	**332.6**	**309.2**	**315.3**	**308.0**	**1.9%**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8	0.7%
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0	27.2%
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2	15.5%
Total	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**	**7.7%**

Note: Totals may not sum due to independent rounding.

Agriculture sector emissions decreased by 1.9 percent since 2021 and increased by 7.7 percent since 1990. Some significant trends in U.S. emissions from Agriculture source categories (Figure 2-10) over the 33-year time series from 1990 through 2022 included the following:

- Agricultural soils are the largest anthropogenic source of agriculture-related emissions and of N_2O emissions in the United States, accounting for 74.6 percent of N_2O emissions and 4.6 percent of total emissions in the United States in 2022. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2022, and overall emissions were 0.7 percent (2.0 MMT CO_2 Eq.) higher in 2022 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.
- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2022, enteric fermentation CH_4 emissions were 27.4 percent of total CH_4 emissions, which represents an increase of 5.2 percent (9.5 MMT CO_2 Eq.) since 1990. This increase in emissions from enteric fermentation from 1990 to 2022 generally follows the increasing trends in cattle populations. For example, from 1990 to 1995, emissions increased and then generally decreased from 1996 to 2004, mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions increased from 2005 to 2007, as both dairy and beef populations increased. Research indicates that the feed digestibility of dairy cow diets decreased during this period. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased. Emissions increased from 2014 to 2022, consistent with an increase in beef cattle population over those same years. CH_4 emissions from enteric fermentation decreased by 2.0 percent (3.9 MMT CO_2 Eq.) from 2021 to 2022, however, largely driven by a decrease in beef cattle populations.
- Manure management is the fourth largest anthropogenic source of CH_4 and N_2O emissions in the United States and accounted for 13.8 percent of Agriculture sector emissions in 2022. Emissions from manure management increased by 55.6 percent between 1990 and 2022. This includes an increase of 65.3 percent (25.6 MMT CO_2 Eq.) for CH_4 and an increase of 27.2 percent (3.6 MMT CO_2 Eq.) for N_2O. The majority of the increase observed in CH_4 emissions resulted from swine and dairy cattle manure, where emissions increased by 37.2 and 108.7 percent, respectively, from 1990 to 2022. From 2021 to 2022, CH_4 emissions from manure management decreased by 2.6 percent, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

- Liming and urea fertilization are the only sources of CO_2 emissions reported in the Agriculture sector. All other CO_2 emissions and removals (e.g., carbon stock changes from the management of croplands) are included in the LULUCF sector. Liming emissions increased by 36.9 percent relative to 2021 and decreased by 30.3 percent (1.4 MMT CO_2 Eq.) relative to 1990, while urea fertilization emissions increased by 1.9 percent relative to 2021 and 120.4 percent (2.9 MMT CO_2 Eq.) relative to 1990.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices, they also influence the carbon stock fluxes on these lands and cause emissions of CH_4 and N_2O. Overall, managed land is a net sink for CO_2 (carbon sequestration) in the United States. The primary driver of fluxes on managed lands is from management of forest lands, but also includes trees in settlements (i.e., urban areas), afforestation, conversion of forest lands to settlements and croplands, the management of croplands and grasslands, flooded lands, and the landfilling of yard trimmings and food scraps. The main drivers for net forest sequestration include net forest growth, increasing forest area, and a net accumulation of carbon stocks in harvested wood pools. The net sequestration in settlements remaining settlements is driven primarily by carbon stock gains in urban forests (i.e., settlement trees) through net tree growth and increased urban area, as well as long-term accumulation of carbon in landfills from additions of yard trimmings and food scraps.

The LULUCF sector in 2022 resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 MMT CO_2 Eq. (Table 2-8).[6] This represents an offset of 14.5 percent of total (i.e., gross) greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 were 67.6 MMT CO_2 Eq. and represented 1.2 percent of net greenhouse gas emissions.[7] Between 1990 and 2022, total net carbon sequestration in the LULUCF sector decreased by 10.9 percent, primarily due to a decrease in the rate of net carbon accumulation in forests and cropland remaining cropland, as well as an increase in CO_2 emissions from land converted to settlements.

Flooded land remaining flooded land was the largest source of CH_4 emissions from LULUCF and the fifth largest source overall of net CH_4 emissions in 2022, totaling 44.2 MMT CO_2 Eq. (1,579 kt of CH_4). Forest fires were the second largest source of CH_4 emissions from LULUCF in 2022, totaling 9.1 MMT CO_2 Eq. (327 kt of CH_4). Forest fires were the largest source of N_2O emissions from LULUCF in 2022, totaling 5.7 MMT CO_2 Eq. (22 kt of N_2O). Figure 2-11 and Table 2-8 illustrate LULUCF emissions and removals by land-use category and gas.

[6] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[7] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

Figure 2-11: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

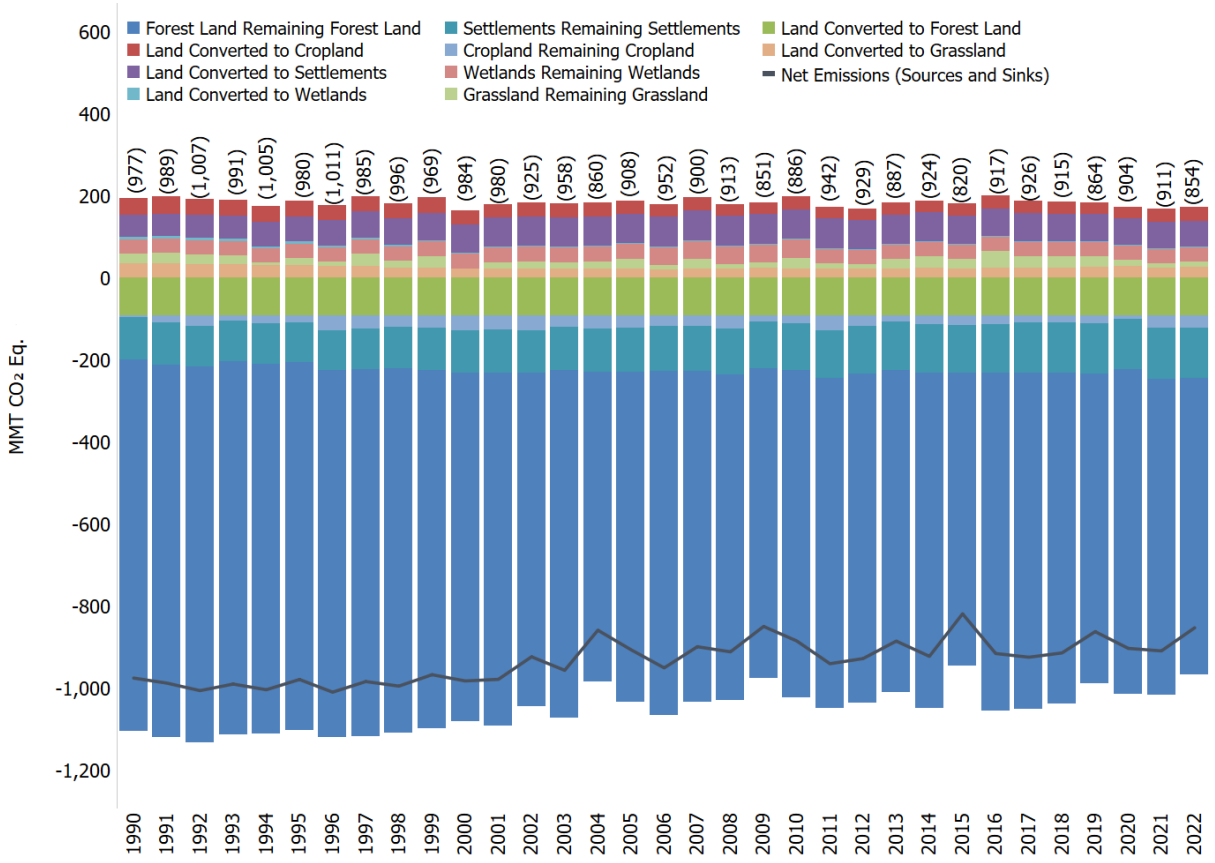


Table 2-8: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
Forest Land Remaining Forest Land	**(968.8)**	**(860.1)**	**(863.4)**	**(807.0)**	**(846.3)**	**(823.9)**	**(771.7)**	**-20.3%**
Changes in Forest Carbon Stocks[a]	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)	-19.3%
Non-CO_2 Emissions from Forest Fires[b]	5.8	15.4	9.7	5.7	15.3	19.9	14.8	153.9%
N_2O Emissions from Forest Soils[c]	0.1	0.4	0.4	0.4	0.4	0.4	0.4	455.1%
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0%
Land Converted to Forest Land	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**	**0.1%**
Changes in Forest Carbon Stocks[e]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)	0.1%
Cropland Remaining Cropland	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**	**529.0%**
Changes in Mineral and Organic Soil Carbon Stocks	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)	529.0%
Land Converted to Cropland	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**	**-22.7%**
Changes in all Ecosystem Carbon Stocks[f]	45.4	34.5	31.9	31.4	29.3	34.9	35.1	-22.7%
Grassland Remaining Grassland	**24.6**	**24.9**	**29.7**	**28.9**	**17.1**	**11.5**	**14.0**	**-43.1%**

Changes in Mineral and Organic Soil Carbon Stocks	24.4	24.1	28.6	28.5	16.1	10.6	13.4	-45.2%
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.8	1.1	0.3	1.1	0.9	0.6	184.1%
Land Converted to Grassland	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**	**-27.3%**
Changes in all Ecosystem Carbon Stocks[f]	35.3	21.8	25.2	25.4	28.7	24.5	25.6	-27.3%
Wetlands Remaining Wetlands	**36.8**	**39.4**	**38.2**	**38.1**	**38.1**	**38.1**	**38.1**	**3.6%**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.6	0.6	0.5	0.6	-45.7%
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+	-47.0%
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(11.1)	(11.1)	(11.1)	(11.1)	(11.1)	2.8%
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3	3.4%
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1	14.9%
CH_4 Emissions from Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2	4.7%
Land Converted to Wetlands	**7.2**	**1.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**-90.3%**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)	-97.0%
CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2	-38.9%
Changes in Land Converted to Flooded Land	3.6	0.6	0.3	0.3	0.3	0.3	0.3	-91.7%
CH_4 Emissions from Land Converted to Flooded Land	2.9	0.4	0.2	0.2	0.2	0.2	0.2	-92.6%
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.0)**	**(131.5)**	**(131.8)**	**(132.3)**	**(132.3)**	**21.2%**
Changes in Organic Soil Carbon Stocks	9.9	10.1	14.4	14.6	15.1	15.4	15.4	56.0%
Changes in Settlement Tree Carbon Stocks	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)	43.4%
N_2O Emissions from Settlement Soils[h]	2.1	3.1	2.4	2.5	2.5	2.5	2.5	22.8%
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(13.4)	(13.1)	(12.8)	(12.5)	(11.8)	-52.0%
Land Converted to Settlements	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**	**19.1%**
Changes in all Ecosystem Carbon Stocks[f]	57.2	77.1	71.4	70.2	68.8	68.2	68.2	19.1%
LULUCF Carbon Stock Change[i]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**	**-10.9%**
LULUCF Emissions[j]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**	**16.5%**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4	10.0%
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1	88.3%
LULUCF Sector Net Total[k]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**	**-12.5%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.
[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.
[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.
[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.
[h] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.
[i] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land-use conversion categories.
[j] LULUCF emissions subtotal includes the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, and land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils. Emissions values are included in land-use category rows.
[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Overall CH_4 and N_2O emissions from LULUCF decreased by 7.3 percent from 2021 and increased by 16.5 percent since 1990 while total net sequestration decreased by 10.9 percent since 1990 and 6.3 percent from 2021. Other trends from 1990 to 2022 in emissions from LULUCF categories (Figure 2-11) over the 33-year period included the following:

- Annual carbon sequestration by forest land (i.e., annual carbon stock accumulation in the five ecosystem carbon pools and harvested wood products for forest land remaining forest land and land converted to forest land) has decreased by 17.5 percent since 1990. This is primarily due to decreased carbon stock gains in land converted to forest land and the harvested wood products pools within forest land remaining forest land.
- Annual carbon sequestration from settlements remaining settlements (which includes organic soils, settlement trees, and landfilled yard trimmings and food scraps) has increased by 21.2 percent over the period from 1990 to 2022. This is primarily due to an increase in urbanized land area in the United States with trees growing on it.
- Annual emissions from land converted to settlements increased by 19.1 percent from 1990 to 2022 due primarily to carbon stock losses from forest land converted to settlements and mineral soils carbon stocks from grassland converted to settlements.

Waste

Waste management and treatment activities are sources of CH_4 and N_2O emissions (see Figure 2-12 and Table 2-9). Overall, emission sources accounted for in the Waste chapter generated 166.9 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions in 2022. In 2022, landfills were the largest source of waste emissions, accounting for 71.8 percent of waste-related emissions. Landfills are also the third-largest source of U.S. anthropogenic CH_4 emissions, generating 119.8 MMT CO_2 Eq. and accounting for 17.1 percent of total U.S. CH_4 emissions in 2022.[8] Additionally, wastewater treatment generated emissions of 42.7 MMT CO_2 Eq. and accounted for 25.6 percent of waste emissions, 3.0 percent of U.S. CH_4 emissions, and 5.6 percent of U.S. N_2O emissions in 2022. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.6 MMT CO_2 Eq. and 1.8 MMT CO_2 Eq., accounting for 1.5 and 1.1 percent of Waste sector emissions, respectively. Anaerobic digestion

[8] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

at biogas facilities generated CH_4 emissions of less than 0.05 MMT CO_2 Eq., accounting for less than 0.05 percent of emissions from the Waste sector.

Figure 2-12: Trends in Waste Sector Greenhouse Gas Sources

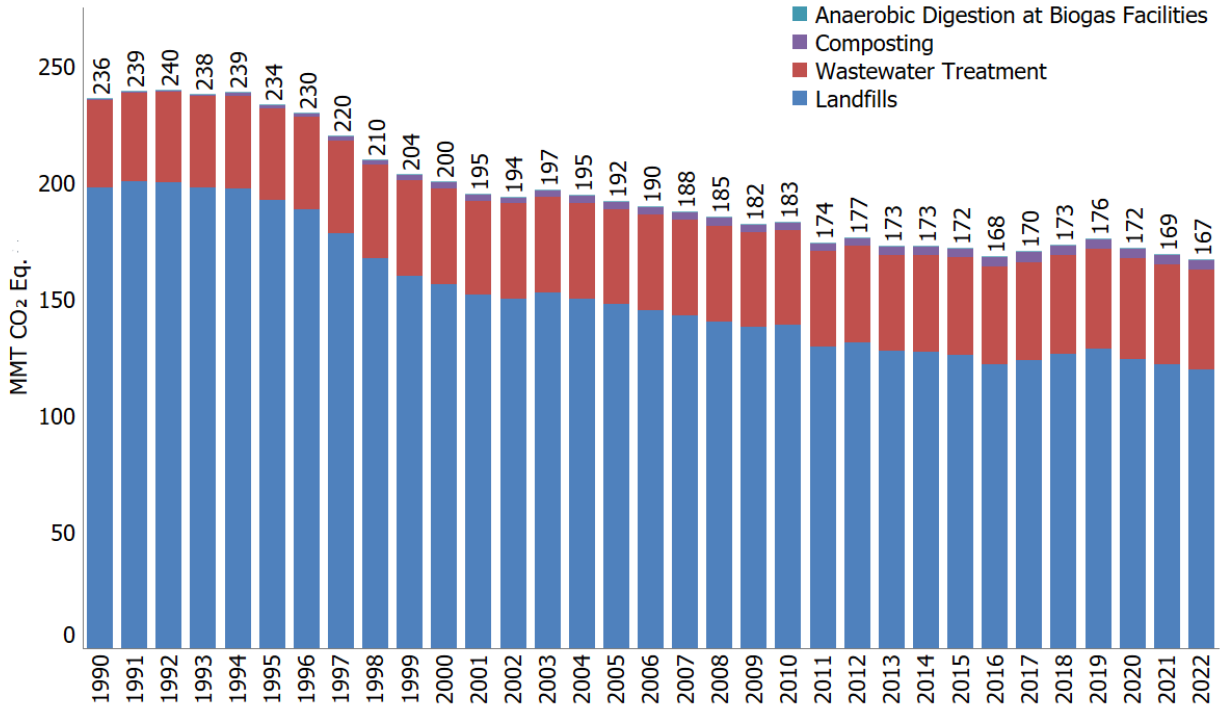


Table 2-9: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022	Percent Change Since 1990
CH_4	**220.9**	**172.4**	**150.2**	**152.4**	**147.6**	**145.3**	**143.2**	**(35.2%)**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8	(39.4%)
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8	(8.4%)
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6	504.8%
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+	1,109.3%
N_2O	**15.1**	**19.5**	**23.0**	**23.4**	**24.1**	**23.9**	**23.7**	**57.4%**
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9	48.2%
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8	504.8%
Total	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**	**(29.3%)**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Waste sector emissions decreased by 1.4 percent since 2021 and 29.3 percent since 1990. Some notable trends in U.S. emissions from Waste source categories (Figure 2-12) over the 33-year period from 1990 through 2022 included the following:

- Net CH_4 emissions from landfills decreased by 78.0 MMT CO_2 Eq. (39.4 percent), with small increases occurring in interim years. This downward trend in emissions coincided with increased landfill gas

collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in municipal solid waste (MSW) landfills over the time series.

- CH_4 and N_2O emissions from wastewater treatment decreased by 8.4 percent (1.9 MMT CO_2 Eq.) and increased by 48.2 percent (7.1 MMT CO_2 Eq.), respectively. Methane emissions from domestic wastewater treatment have decreased since 1999 due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. N_2O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.
- Combined CH_4 and N_2O emissions from composting have increased by 504.8 percent (3.7 MMT CO_2 Eq.) since 1990. The growth in composting since the 1990s is attributable to primarily four factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills; (2) an increase in yard trimming collection and yard trimming drop-off sites provided by local solid waste management districts; (3) an increased awareness of the environmental benefits of composting; and (4) loans or grant programs to establish or expand composting infrastructure.

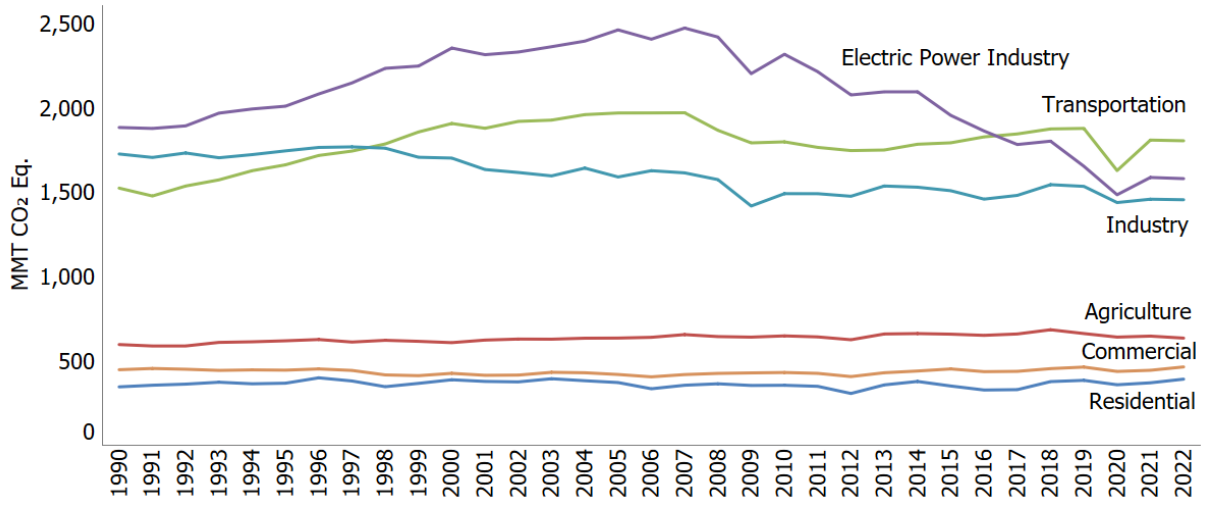
2.2 Emissions and Sinks by Economic Sector

In addition to the Paris Agreement and UNFCCC reporting sectors and methods defined by the IPCC, this report also characterizes gross emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. See Box 2-1 for more information on how economic sectors are defined. For more information on trends in the LULUCF sector, see Section 2.1.

Using this categorization, transportation activities accounted for the largest portion (28.4 percent) of total U.S. greenhouse gas emissions in 2022. Emissions from electric power accounted for the second largest portion (24.9 percent), while emissions from industry accounted for the third-largest portion (22.9 percent) of total U.S. greenhouse gas emissions in 2022. Emissions from industry have in general declined over the past decade due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

The remaining 23.8 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.0 percent of emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. An increasing amount of carbon is stored in agricultural soils each year, but this carbon sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for roughly 7.3 percent and 6.2 percent of greenhouse gas emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered (in the form of carbon) by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in carbon stocks in coastal wetlands. Table 2-10 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-13 shows the trend in emissions by sector from 1990 to 2022.

Figure 2-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq. and Percent of Total in 2022)

Sector/Source	1990	2005	2018	2019	2020	2021	2022	Percent of Total Emissions[a]
Transportation	**1,521.4**	**1,965.9**	**1,871.6**	**1,874.6**	**1,625.3**	**1,805.5**	**1,801.5**	**28.4%**
CO_2 from Fossil Fuel Combustion	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3	27.6%
Substitution of Ozone Depleting Substances	+	63.1	35.5	34.0	32.5	31.2	29.6	0.5%
Mobile Combustion[b]	40.6	34.1	13.7	15.1	12.2	12.7	12.2	0.2%
Non-Energy Use of Fuels	11.8	10.2	9.2	8.8	7.8	8.0	8.4	0.1%
Electric Power Industry	**1,880.2**	**2,457.4**	**1,799.2**	**1,650.8**	**1,482.2**	**1,584.4**	**1,577.5**	**24.9%**
CO_2 from Fossil Fuel Combustion	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7	24.1%
Stationary Combustion[b]	18.7	27.7	23.1	20.2	18.9	20.4	22.9	0.4%
Incineration of Waste	13.3	13.6	13.7	13.3	13.3	12.8	12.7	0.2%
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2	0.1%
Electrical Equipment	24.7	11.9	5.0	6.1	5.9	6.0	5.1	0.1%
Industry	**1,723.3**	**1,587.3**	**1,541.9**	**1,531.8**	**1,435.9**	**1,455.8**	**1,452.5**	**22.9%**
CO_2 from Fossil Fuel Combustion	833.1	796.8	770.7	770.1	722.9	740.7	761.8	12.0%
Natural Gas Systems	251.2	236.5	223.0	227.3	217.0	210.4	209.7	3.3%
Non-Energy Use of Fuels	83.9	107.2	108.9	97.4	89.9	103.5	94.3	1.5%
Petroleum Systems	59.0	58.5	93.8	97.8	82.3	72.8	61.6	1.0%
Coal Mining	112.7	75.6	62.2	56.0	48.3	47.1	46.1	0.7%
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9	0.7%
Iron and Steel Production	104.8	70.1	42.9	43.1	37.7	41.9	40.7	0.6%
Substitution of Ozone Depleting Substances	+	8.0	31.9	33.1	33.9	32.2	33.4	0.5%

Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8	0.5%
Landfills (Industrial)	12.2	16.1	18.7	18.8	18.9	18.9	18.9	0.3%
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6	0.2%
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2	0.2%
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6	0.1%
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5	0.1%
Fluorochemical Production	70.9	30.0	8.7	9.3	6.9	7.1	7.8	+%
Wastewater Treatment	6.6	7.1	7.5	7.6	7.6	7.6	7.7	+%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1	+%
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3	+%
Mobile Combustion[b]	3.6	5.6	5.5	5.6	5.3	5.5	5.9	+%
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2	+%
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0	+%
Electronics Industry	3.3	4.5	4.8	4.5	4.5	4.8	4.7	+%
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8	+%
Stationary Combustion[b]	4.8	4.5	3.9	3.8	3.6	3.6	3.5	+%
Aluminum Production	26.1	7.2	2.9	3.3	3.2	2.5	2.2	+%
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1	+%
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0	+%
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7	+%
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5	+%
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3	+%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3	+%
Magnesium Production and Processing	5.7	3.0	1.1	1.0	0.9	1.2	1.2	+%
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9	+%
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8	+%
SF_6 and PFCs from Other Product Use	1.4	1.5	0.9	0.8	0.7	0.5	0.8	+%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4	+%
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2	+%
Agriculture	**595.9**	**634.3**	**683.5**	**661.0**	**640.0**	**645.9**	**634.0**	**10.0%**
N_2O from Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8	4.6%
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6	3.0%
Manure Management	52.5	70.2	84.3	83.5	83.8	83.6	81.7	1.3%
CO_2 from Fossil Fuel Combustion	43.4	50.8	39.8	39.7	39.1	39.8	39.3	0.6%
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9	0.3%
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3	0.1%
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3	0.1%

Mobile Combustion[b]	1.4	1.6	1.2	1.2	1.2	1.2	1.2	+%
Field Burning of Agricultural Residues	0.7	0.8	0.8	0.9	0.8	0.8	0.8	+%
Stationary Combustion[b]	0.1	+	0.1	0.1	0.1	0.1	0.1	+%
Commercial	**447.0**	**418.9**	**453.5**	**462.6**	**436.9**	**443.7**	**463.7**	**7.3%**
CO_2 from Fossil Fuel Combustion	228.3	227.1	246.3	251.7	229.3	237.5	258.7	4.1%
Landfills (Municipal)	185.5	131.6	107.7	109.9	105.2	103.1	100.9	1.6%
Substitution of Ozone Depleting Substances	+	21.4	58.5	59.8	60.8	61.9	62.9	1.0%
Wastewater Treatment	30.9	33.6	35.0	35.1	35.6	35.1	35.0	0.6%
Composting	0.7	3.6	4.3	4.3	4.4	4.4	4.4	0.1%
Stationary Combustion[b]	1.5	1.5	1.7	1.7	1.6	1.6	1.7	0.0%
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+	+%
Residential	**345.6**	**371.2**	**376.8**	**384.2**	**358.0**	**369.6**	**391.3**	**6.2%**
CO_2 from Fossil Fuel Combustion	338.6	358.9	338.9	342.9	314.8	318.0	334.1	5.3%
Substitution of Ozone Depleting Substances	0.2	7.0	31.9	35.1	39.0	47.3	52.2	0.8%
Stationary Combustion[b]	6.8	5.3	6.0	6.2	4.2	4.2	5.0	0.1%
U.S. Territories	**23.4**	**59.7**	**26.3**	**25.1**	**23.4**	**23.9**	**22.7**	**0.4%**
CO_2 from Fossil Fuel Combustion	20.0	51.9	25.9	24.8	23.3	23.8	22.6	0.4%
Non-Energy Use of Fuels	3.4	7.6	0.2	0.2	0.1	0.1	0.1	+%
Stationary Combustion[b]	0.1	0.2	0.1	0.1	0.1	0.1	0.1	+%
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**100.0%**
LULUCF Sector Net Total[c]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**	**(13.5%)**
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**86.5%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for 2022.

[b] Includes CH_4 and N_2O emissions from fuel combustion.

[c] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.

Notes: Total gross emissions presented are without LULUCF. Total net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Box 2-1: Methodology for Aggregating Emissions by Economic Sector

In presenting the economic sectors in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, the *Inventory* expands upon the standard sectors common for reporting under the Paris Agreement and the UNFCCC. Discussing greenhouse gas emissions relevant to U.S.-specific economic sectors improves communication of the report's findings.

The electric power economic sector includes CO_2, CH_4 and N_2O emissions from the combustion of fossil fuels that are included in the EIA electric power sector. Carbon dioxide, CH_4, and N_2O emissions from waste incineration are included in the electric power economic sector, as the majority of MSW is combusted in plants that produce electricity. The electric power economic sector also includes SF_6 from electrical equipment, and a portion of CO_2 from other process uses of carbonates (from pollution control equipment installed in electric power plants).

The transportation economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA transportation fuel-consuming sector. (Additional analyses and refinement of the EIA data are further explained in the Energy chapter of this report.) Emissions of CH_4 and N_2O from mobile combustion are also

apportioned to the transportation economic sector based on the EIA transportation fuel-consuming sector. Emissions of ODS substitutes are apportioned to the transportation economic sector based on emissions from refrigerated transport and motor vehicle air-conditioning systems. Finally, CO_2 emissions from non-energy uses of fossil fuels identified as lubricants for transportation vehicles are included in the transportation economic sector.

The industry economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA industrial fuel-consuming sector, minus the agricultural use of fuel explained below. The CH_4 and N_2O emissions from stationary and mobile combustion are also apportioned to the industry economic sector based on the EIA industrial fuel-consuming sector, minus emissions apportioned to the agriculture economic sector. Emissions of ODS substitutes are apportioned based on their specific end-uses within the source category, with most emissions falling within the industry economic sector. Finally, CH_4 emissions from industrial landfills and CH_4 and N_2O from industrial wastewater treatment are included in the industry economic sector.

Additionally, all process-related emissions from sources with methods considered within the IPCC IPPU sector are apportioned to the industry economic sector. This includes the process-related emissions (i.e., emissions from the actual process to make the material, not from fuels to power the plant) from activities such as cement production, iron and steel production and metallurgical coke production, and ammonia production. Additionally, fugitive emissions from energy production sources, such as natural gas systems, coal mining, and petroleum systems are included in the industry economic sector. A portion of CO_2 from other process uses of carbonates (from pollution control equipment installed in large industrial facilities) is also included in the industry economic sector. Finally, all remaining CO_2 emissions from non-energy uses of fossil fuels are assumed to be industrial in nature (besides the lubricants for transportation vehicles specified above) and are attributed to the industry economic sector.

The agriculture economic sector includes CO_2 emissions from the combustion of fossil fuels that are based on supplementary sources of agriculture fuel use data, because EIA includes agriculture equipment in the industrial fuel-consuming sector. Agriculture fuel use estimates are obtained from U.S. Department of Agriculture survey data, in combination with EIA Fuel Oil and Kerosene Sales (FOKS) data (EIA 1991 through 2022). Agricultural operations are based on annual energy expense data from the Agricultural Resource Management Survey (ARMS) conducted by the National Agricultural Statistics Service (NASS) of the USDA. NASS collects information on farm production expenditures including expenditures on diesel fuel, gasoline, LP gas, natural gas, and electricity use on the farm with the annual ARMS. A USDA publication (USDA/NASS 2023) shows national totals, as well as selected States and ARMS production regions. These supplementary data are subtracted from the industrial fuel use reported by EIA to obtain agriculture fuel use. Carbon dioxide emissions from fossil fuel combustion, and CH_4 and N_2O emissions from stationary and mobile combustion, are then apportioned to the agriculture economic sector based on agricultural fuel use.

The other IPCC Agriculture emission source categories apportioned to the agriculture economic sector include N_2O emissions from agricultural soils, CH_4 from enteric fermentation, CH_4 and N_2O from manure management, CH_4 from rice cultivation, CO_2 emissions from liming and urea application, and CH_4 and N_2O from field burning of agricultural residues.

The residential economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA residential fuel-consuming sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel-consuming sector. Emissions of ODS substitutes are apportioned to the residential economic sector based on emissions from residential air-conditioning systems. N_2O emissions from the application of fertilizers to developed land (termed “settlements” by the IPCC) are also included in the residential economic sector.

The commercial economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA commercial fuel-consuming sector. Emissions of CH_4 and N_2O from mobile combustion are also apportioned to the commercial economic sector based on the EIA commercial fuel-consuming sector. Emissions of ODS substitutes are apportioned to the commercial economic sector based on emissions from commercial refrigeration/air-conditioning systems. Public works sources, including direct CH_4 from municipal landfills, CH_4

from anaerobic digestion at biogas facilities, CH_4 and N_2O from domestic wastewater treatment, and composting, are also included in the commercial economic sector.

Emissions with Electricity Distributed to Economic Sectors

It is also useful to view greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from the electric power sector are allocated to the economic end-use sectors in which the electricity is used). For example, greenhouse gas emissions from some economic sectors, i.e., commercial and residential and industry, increase substantially when indirect emissions from electricity end-use are included, due to the relatively large share of electricity use by buildings (75 percent of the electricity generated in the United States for heating, ventilation, and air conditioning; lighting; and appliances, etc.)[9] and use of electricity for powering industrial machinery.

The generation, transmission, and distribution of electricity directly accounted for 24.9 percent of total U.S. greenhouse gas emissions in 2022. Electric power-related emissions decreased by 16.1 percent since 1990 mainly due to fuel switching in the electric power sector. From 2021 to 2022, electric power-related emissions decreased by 0.4 percent. Between 2021 and 2022, the consumption of natural gas and petroleum for electric power generation increased by 7.6 percent and 18.9 percent, respectively, while the consumption of coal decreased by 6.4 percent. Electric power-related emissions are still lower than pre-pandemic 2019 levels. Table 2-11 provides a detailed summary of emissions from electric power-related activities.

From 2021 to 2022, electricity sales to the residential end-use sector increased by 2.6 percent. Electricity sales to the commercial end-use and industrial sectors increased by 4.7 percent and 2.0 percent, respectively. Overall, from 2021 to 2022, the amount of electricity retail sales (in kWh) increased by 3.2 percent.

Table 2-11: Electric Power-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Fuel Type or Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**1,836.4**	**2,417.5**	**1,770.7**	**1,624.2**	**1,457.0**	**1,557.7**	**1,549.2**
Fossil Fuel Combustion	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7
Coal	*1,546.5*	*1,982.8*	*1,152.9*	*973.5*	*788.2*	*910.1*	*851.5*
Natural Gas	*175.4*	*318.9*	*577.9*	*616.6*	*634.8*	*612.8*	*659.3*
Petroleum	*97.5*	*98.0*	*22.2*	*16.2*	*16.2*	*17.7*	*20.5*
Geothermal	*0.5*	*0.5*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Other Process Uses of Carbonates	3.6	4.2	4.0	4.5	4.5	4.3	5.2
CH_4	**0.5**	**1.0**	**1.4**	**1.4**	**1.4**	**1.4**	**1.3**
Stationary Sources[a]	0.5	1.0	1.4	1.4	1.4	1.4	1.3
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**18.6**	**27.1**	**22.1**	**19.1**	**17.9**	**19.4**	**21.9**
Stationary Sources[a]	18.2	26.7	21.7	18.8	17.5	19.0	21.6
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
SF_6	**24.7**	**11.8**	**5.0**	**6.1**	**5.9**	**6.0**	**5.1**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
CF_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	+	+	+	+	+	+	+
Total	**1,880.2**	**2,457.4**	**1,799.2**	**1,650.8**	**1,482.2**	**1,584.4**	**1,577.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

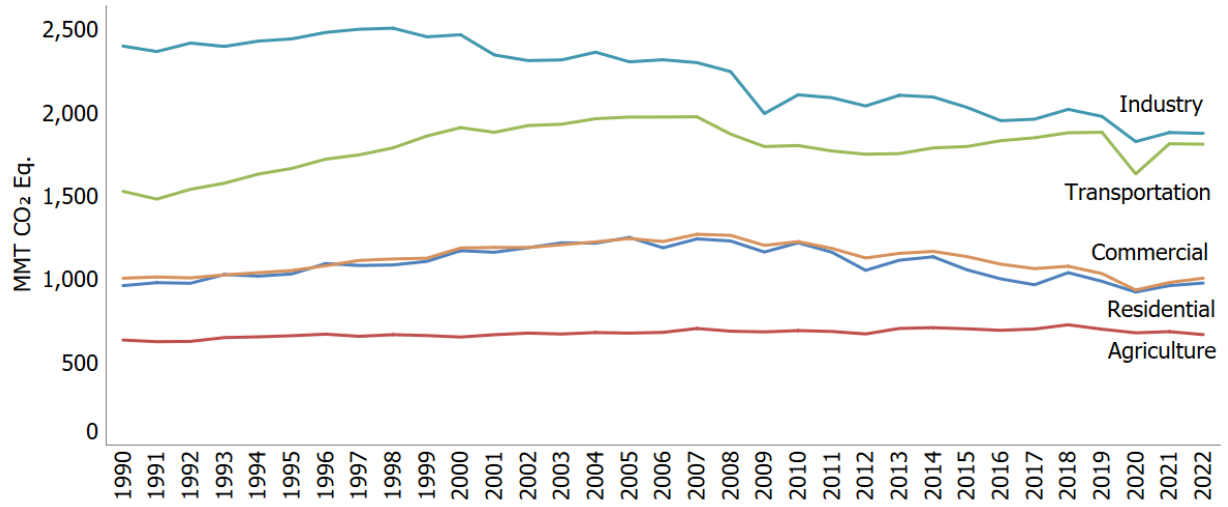
[9] See https://www.nrel.gov/news/features/2023/nrel-researcher-reveal-how-buildings-across-the-united-states-do-and-could-use-energy.html#:~:text=Buildings%20are%20responsible%20for%2040,buildings%20stock%20is%20also%20essential.

[a] Includes only stationary combustion emissions related to the generation of electricity.
Note: Totals may not sum due to independent rounding.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electric power sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to each economic sector's share of retail sales of electricity (EIA 2020; USDA/NASS 2023). These source categories include CO_2 from fossil fuel combustion, CH_4 and N_2O from stationary combustion, incineration of waste, other process uses of carbonates, and SF_6 from electrical equipment. Note that only 50 percent of the emissions from other process uses of carbonates were associated with electric power and distributed as described; the remaining emissions from other process uses of carbonates were attributed to the industry economic end-use sector.[10]

When emissions from electricity use are distributed among these economic end-use sectors, 2022 emissions from industrial activities account for the largest share of total U.S. greenhouse gas emissions (29.5 percent), followed closely by emissions from transportation (28.5 percent). Emissions from the commercial and residential sectors also increase substantially when emissions from electricity are included (15.8 and 15.3 percent, respectively). In all economic end-use sectors except agriculture, CO_2 accounts for more than 78 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Table 2-12 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electric power distributed to them. Figure 2-14 shows the trend in these emissions by sector from 1990 to 2022.

Figure 2-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-12: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (MMT CO_2 Eq.) and Percent of Total in 2022

Emissions by Gas	1990	2005	2018	2019	2020	2021	2022	Percent[a]
Industry	**2,397.3**	**2,302.9**	**2,017.1**	**1,974.8**	**1,823.5**	**1,877.8**	**1,872.9**	**29.5%**
Direct Emissions	**1,723.3**	**1,587.3**	**1,541.9**	**1,531.8**	**1,435.9**	**1,455.8**	**1,452.5**	**22.9%**

[10] Emissions were not distributed to U.S. Territories, since the electric power sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

CO_2	1,173.8	1,136.4	1,110.7	1,118.3	1,036.9	1,071.1	1,080.8	17.0%
CH_4	413.3	371.2	352.2	337.7	323.3	311.3	299.8	4.7%
N_2O	35.7	29.8	30.3	26.0	27.6	26.8	23.6	0.4%
HFCs, PFCs, SF_6 and NF_3	100.6	49.8	48.6	49.8	48.1	46.5	48.3	0.8%
Electricity-Related	**674.0**	**715.6**	**475.3**	**443.0**	**387.6**	**422.0**	**420.3**	**6.6%**
CO_2	658.3	704.0	467.7	435.9	381.0	414.9	412.8	6.5%
CH_4	0.2	0.3	0.4	0.4	0.4	0.4	0.3	+%
N_2O	6.7	7.9	5.8	5.1	4.7	5.2	5.8	0.1%
SF_6	8.8	3.5	1.3	1.6	1.5	1.6	1.4	+%
Transportation	**1,524.6**	**1,970.8**	**1,876.5**	**1,879.5**	**1,629.5**	**1,810.6**	**1,807.8**	**28.5%**
Direct Emissions	**1,521.4**	**1,965.9**	**1,871.6**	**1,874.6**	**1,625.3**	**1,805.5**	**1,801.5**	**28.4%**
CO_2	1,480.8	1,868.7	1,822.3	1,825.5	1,580.6	1,761.6	1,759.7	27.7%
CH_4	6.4	3.1	1.7	1.7	1.4	1.5	1.5	+%
N_2O	34.3	31.0	12.1	13.4	10.7	11.2	10.7	0.2%
HFCs[b]	+	63.1	35.5	34.0	32.5	31.2	29.6	0.5%
Electricity-Related	**3.1**	**4.8**	**4.9**	**4.9**	**4.2**	**5.2**	**6.3**	**0.1%**
CO_2	3.1	4.8	4.8	4.9	4.1	5.1	6.2	0.1%
CH_4	+	+	+	+	+	+	+	+%
N_2O	+	0.1	0.1	0.1	0.1	0.1	0.1	+%
SF_6	+	+	+	+	+	+	+	+%
Residential	**958.0**	**1,247.7**	**1,035.9**	**984.0**	**919.5**	**958.0**	**973.5**	**15.3%**
Direct Emissions	**345.6**	**371.2**	**376.8**	**384.2**	**358.0**	**369.6**	**391.3**	**6.2%**
CO_2	338.6	358.9	338.9	342.9	314.8	318.0	334.1	5.3%
CH_4	5.9	4.5	5.1	5.3	3.6	3.6	4.3	0.1%
N_2O	0.9	0.8	0.8	0.8	0.6	0.6	0.7	+%
SF_6	0.2	7.0	31.9	35.1	39.0	47.3	52.2	0.8%
Electricity-Related	**612.4**	**876.5**	**659.1**	**599.7**	**561.5**	**588.4**	**582.2**	**9.2%**
CO_2	598.1	862.2	648.6	590.1	551.9	578.5	571.8	9.0%
CH_4	0.2	0.3	0.5	0.5	0.5	0.5	0.5	+%
N_2O	6.1	9.7	8.1	6.9	6.8	7.2	8.1	0.1%
SF_6	8.0	4.2	1.8	2.2	2.2	2.2	1.9	+%
Commercial	**1,002.5**	**1,241.1**	**1,074.3**	**1,030.5**	**931.5**	**976.8**	**1,002.6**	**15.8%**
Direct Emissions	**447.0**	**418.9**	**453.5**	**462.6**	**436.9**	**443.7**	**463.7**	**7.3%**
CO_2	228.3	227.1	246.3	251.7	229.3	237.5	258.7	4.1%
CH_4	203.6	150.9	125.9	127.8	122.9	120.5	118.5	1.9%
N_2O	15.1	19.4	22.8	23.2	23.9	23.7	23.6	0.4%
HFCs	+	21.4	58.5	59.8	60.8	61.9	62.9	1.0%
Electricity-Related	**555.5**	**822.2**	**620.8**	**567.8**	**494.6**	**533.2**	**539.0**	**8.5%**
CO_2	542.6	808.9	611.0	558.7	486.2	524.2	529.3	8.3%
CH_4	0.1	0.3	0.5	0.5	0.5	0.5	0.4	+%
N_2O	5.5	9.1	7.6	6.6	6.0	6.5	7.5	0.1%
SF_6	7.3	4.0	1.7	2.1	2.0	2.0	1.7	+%
Agriculture	**631.1**	**672.6**	**722.7**	**696.3**	**674.4**	**681.6**	**663.6**	**10.5%**
Direct Emissions	**595.9**	**634.3**	**683.5**	**661.0**	**640.0**	**645.9**	**634.0**	**10.0%**
CO_2	50.5	58.7	47.0	46.9	47.1	47.4	47.9	0.8%
CH_4	241.9	264.6	285.2	280.4	282.6	282.0	277.0	4.4%
N_2O	303.5	311.0	351.3	333.7	310.3	316.4	309.1	4.9%
Electricity-Related	**35.2**	**38.3**	**39.2**	**35.2**	**34.4**	**35.7**	**29.7**	**0.5%**
CO_2	34.3	37.7	38.6	34.7	33.8	35.1	29.2	0.5%
CH_4	+	+	+	+	+	+	+	+%
N_2O	0.3	0.4	0.5	0.4	0.4	0.4	0.4	+%
SF_6	0.5	0.2	0.1	0.1	0.1	0.1	0.1	+%
U.S. Territories	**23.4**	**59.7**	**26.3**	**25.1**	**23.4**	**23.9**	**22.7**	**0.4%**
Total Gross Emissions (Sources)	**6,536.9**	**7,494.6**	**6,752.7**	**6,590.1**	**6,001.8**	**6,328.8**	**6,343.2**	**100.0%**
LULUCF Sector Net Total[c]	(976.7)	(907.7)	(915.5)	(863.6)	(904.4)	(910.6)	(854.2)	(13.5%)
Net Emissions (Sources and Sinks)	**5,560.2**	**6,586.9**	**5,837.3**	**5,726.6**	**5,097.4**	**5,418.2**	**5,489.0**	**86.5%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.
[a] Percent of total (gross) emissions excluding emissions from LULUCF for the year 2022.
[b] Includes primarily HFC-134a.
[c] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes.
Notes: Total gross emissions are presented without LULUCF. Net emissions are presented with LULUCF. Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding.

Industry

The industry economic sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate, and with the distribution of electricity-related emissions (e.g., powering industrial machinery), accounted for 29.5 percent of U.S. greenhouse gas emissions in 2022. This end-use sector also includes emissions that are produced as a byproduct of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions includes CH_4 emissions from petroleum and natural gas systems, fugitive CH_4 and CO_2 emissions from coal mining, byproduct CO_2 emissions from cement production, and HFC, PFC, SF_6, and NF_3 byproduct emissions from the electronics industry, to name a few.

Since 1990, industry sector emissions have declined by 21.9 percent. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. Structural changes within the U.S. economy that led to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., shifts from producing steel to computer equipment) have had a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 28.5 percent of U.S. greenhouse gas emissions in 2022. The largest sources of transportation greenhouse gas emissions in 2022 were light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (36.5 percent); medium- and heavy-duty trucks (22.9 percent); passenger cars (20.4 percent); commercial aircraft (7.2 percent); pipelines (3.8 percent); ships and boats (2.8 percent); other aircraft (2.0 percent), and rail (2.0 percent). These figures include direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion used in transportation, indirect emissions from electricity use, and emissions from non-energy use (i.e., lubricants) used in transportation, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types.

From 1990 to 2022, total transportation emissions from fossil fuel combustion increased by 19.4 percent due, in large part, to increased demand for travel. From 2021 to 2022, emissions decreased by 0.1 percent. Vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) increased by 46.7 percent from 1990 to 2022 as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 19.4 percent from 1990 to 2022 when including electricity. This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 29.6 MMT CO_2 Eq. in 2022, led to an increase in overall greenhouse gas emissions from transportation activities of 18.6 percent.

The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from approximately 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly between 2005 and 2013. Light-duty VMT grew by less than one percent or declined each year between 2005 and 2013, then grew at a faster rate until 2016 (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Since 2016, the rate of light-duty VMT growth has slowed to one percent or less each year. Average new vehicle fuel economy has increased almost every year since 2005, while light-duty truck market share decreased to

33.0 percent in 2009 and has since varied from year to year between 35.6 and 63.1 percent. Light-duty truck market share was about 63.1 percent of new vehicles in model year 2022 (EPA 2023b).

Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals. Historically, the majority of electricity use in the transportation sector was for rail transport. However, more recently there has been increased electricity use in on-road electric and plug-in hybrid vehicles. Despite this increase, almost all of the energy used for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. Indirect emissions from electricity are less than 1 percent of direct emissions in the transportation sector. For a more detailed breakout of emissions by fuel type by vehicle see Table A-93 in Annex 3.

Figure 2-15: Trends in Transportation-Related Greenhouse Gas Emissions

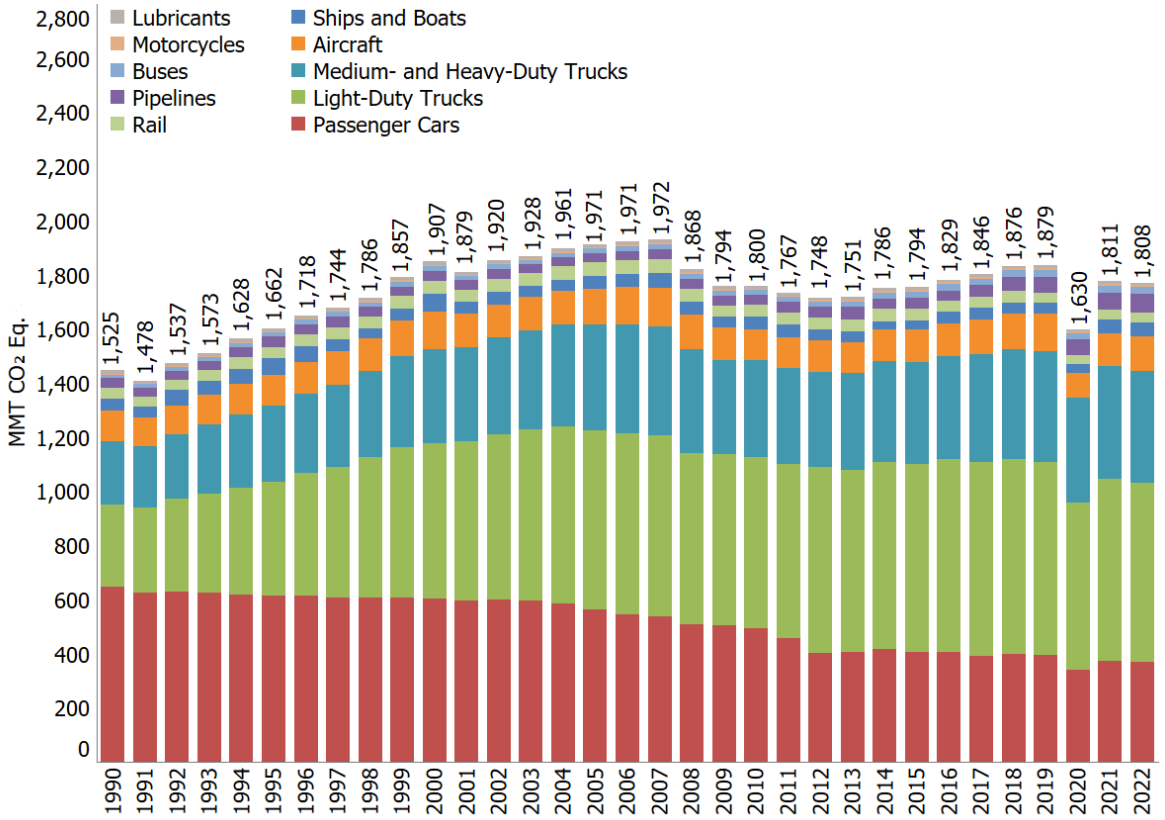


Table 2-13: Transportation-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Vehicle Type	1990	2005	2018	2019	2020	2021	2022
Passenger Cars	**648.4**	**564.4**	**398.7**	**395.5**	**341.7**	**374.2**	**369.5**
CO_2	622.2	521.1	386.5	384.2	331.9	365.0	361.0
CH_4	3.8	1.2	0.3	0.3	0.3	0.3	0.2
N_2O	22.5	13.3	2.5	2.6	2.0	1.9	1.7
HFCs	0.0	28.8	9.4	8.4	7.6	7.0	6.6
Light-Duty Trucks	**302.4**	**659.3**	**720.6**	**711.7**	**615.3**	**671.7**	**660.2**
CO_2	292.1	614.0	699.0	690.1	596.2	654.0	644.5
CH_4	1.5	1.0	0.6	0.6	0.5	0.5	0.5
N_2O	8.7	14.0	4.6	5.6	4.4	4.2	3.8
HFCs	0.0	30.2	16.4	15.4	14.2	13.0	11.4

Medium- and Heavy-Duty Trucks	**234.5**	**391.0**	**406.5**	**409.3**	**386.7**	**417.0**	**413.1**
CO_2	233.1	386.2	397.9	400.3	377.8	407.7	403.6
CH_4	0.5	0.2	0.1	0.1	0.1	0.1	0.1
N_2O	1.0	1.5	2.8	3.0	2.7	3.0	3.1
HFCs	0.0	3.2	5.6	5.8	6.1	6.3	6.3
Buses	**13.3**	**17.8**	**24.9**	**25.3**	**24.0**	**26.1**	**26.3**
CO_2	13.2	17.5	24.3	24.7	23.4	25.6	25.7
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.2	0.2	0.2	0.2	0.2
HFCs	0.0	0.2	0.4	0.4	0.4	0.4	0.4
Motorcycles	**3.4**	**5.0**	**7.4**	**7.5**	**6.7**	**7.5**	**7.6**
CO_2	3.4	4.9	7.3	7.4	6.6	7.4	7.4
CH_4	+	+	+	+	+	+	+
N_2O	+	+	0.1	0.1	0.1	0.1	0.1
Commercial Aircraft[a]	**110.8**	**133.8**	**130.7**	**137.8**	**92.0**	**120.0**	**130.8**
CO_2	109.9	132.7	129.6	136.7	91.3	119.0	129.7
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	0.9	1.1	1.1	1.1	0.7	1.0	1.1
Other Aircraft[b]	**78.0**	**59.5**	**44.6**	**45.6**	**31.0**	**35.5**	**37.0**
CO_2	77.3	59.0	44.2	45.2	30.7	35.1	36.7
CH_4	0.1	0.1	+	+	+	+	+
N_2O	0.6	0.5	0.4	0.4	0.2	0.3	0.3
Ships and Boats[c]	**47.0**	**45.5**	**41.1**	**40.0**	**32.2**	**50.7**	**49.9**
CO_2	46.3	44.3	36.9	35.5	27.5	45.4	44.4
CH_4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
N_2O	0.2	0.2	0.2	0.2	0.1	0.3	0.3
HFCs	0.0	0.5	3.6	3.9	4.2	4.5	4.8
Rail	**39.0**	**51.4**	**42.5**	**39.7**	**34.2**	**35.5**	**35.6**
CO_2	38.5	50.8	41.9	39.1	33.7	34.9	35.0
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.4	0.3	0.3	0.3	0.3	0.3
HFCs	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Emissions from Electric Power[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pipelines[e]	**36.0**	**32.8**	**50.3**	**58.3**	**58.0**	**64.4**	**69.3**
CO_2	36.0	32.8	50.3	58.3	58.0	64.4	69.3
Lubricants	**11.8**	**10.2**	**9.2**	**8.8**	**7.8**	**8.0**	**8.4**
CO_2	11.8	10.2	9.2	8.8	7.8	8.0	8.4
Total Transportation	**1,524.6**	**1,970.8**	**1,876.5**	**1,879.5**	**1,629.5**	**1,810.6**	**1,807.8**
International Bunker Fuels[f]	*54.7*	*44.6*	*32.4*	*26.2*	*22.7*	*22.7*	*25.3*
Ethanol CO_2[g]	*4.1*	*21.6*	*78.6*	*78.7*	*68.1*	*75.4*	*75.0*
Biodiesel CO_2[g]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Consists of emissions from jet fuel consumed by domestic operations of commercial aircraft (no bunkers).

[b] Consists of emissions from jet fuel and aviation gasoline consumption by general aviation and military aircraft.

[c] Fluctuations in emission estimates are associated with fluctuations in reported fuel consumption and may reflect issues with data sources.

[d] Other emissions from electric power are a result of waste incineration (as the majority of MSW is combusted in "trash-to-steam" electric power plants), electrical equipment, and a portion of other process uses of carbonates (from pollution control equipment installed in electric power plants).

[e] CO_2 estimates reflect natural gas used to power pipelines, but not electricity. While the operation of pipelines produces CH_4 and N_2O, these emissions are not directly attributed to pipelines in the Inventory.

[f] Emissions from International Bunker Fuels include emissions from both civilian and military activities; these emissions are not included in the transportation totals.

[g] Ethanol and biodiesel CO_2 estimates are presented for informational purposes only. See Section 3.11 and the estimates in LULUCF (see Chapter 6), in line with IPCC methodological guidance and reporting obligations under the Paris Agreement and the UNFCCC, for more information on ethanol and biodiesel.

Notes: Passenger cars and light-duty trucks include vehicles typically used for personal travel and less than 8,500 lbs; medium- and heavy-duty trucks include vehicles larger than 8,500 lbs. HFC emissions primarily reflect HFC-134a. Totals may not sum due to independent rounding.

Residential

The residential end-use sector, including electricity-related emissions, accounted for 15.3 percent of U.S. greenhouse gas emissions in 2022. This sector is heavily reliant on electricity for meeting energy needs, with electricity use for building-related activities like lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Emissions from the residential sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in housing and building attributes (e.g., larger sizes and improved insulation). A shift toward energy-efficient products and more stringent energy efficiency standards for household equipment has also contributed to recent trends in energy demand in households.

Commercial

The commercial end-use sector, including electricity-related emissions, accounted for 15.8 percent of U.S. greenhouse gas emissions in 2022. Like the residential sector it is heavily reliant on electricity for meeting energy needs, with electricity use for building-related activities like lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Energy-related emissions from the commercial sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Decreases in energy-related emissions in the commercial sector in recent years can be largely attributed to an overall reduction in energy use driven by a reduction in heating degree days and increases in energy efficiency.

Municipal landfills and wastewater treatment are included in the commercial sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions increasing slightly.

Agriculture

The agriculture end-use sector accounted for 10.5 percent of U.S. greenhouse gas emissions in 2022 when electricity-related emissions are distributed, and includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2022, agricultural soil management was the largest source of N_2O emissions, and enteric fermentation was the largest source of CH_4 emissions in the United States. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment such as tractors. Indirect emissions from electricity use in agricultural activities (e.g., powering buildings and equipment) are about 5 percent of direct emissions.

Box 2-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total (gross) greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) aggregate energy use, because energy-related activities are the largest sources of emissions; (2) energy use per capita as a measure of efficiency; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

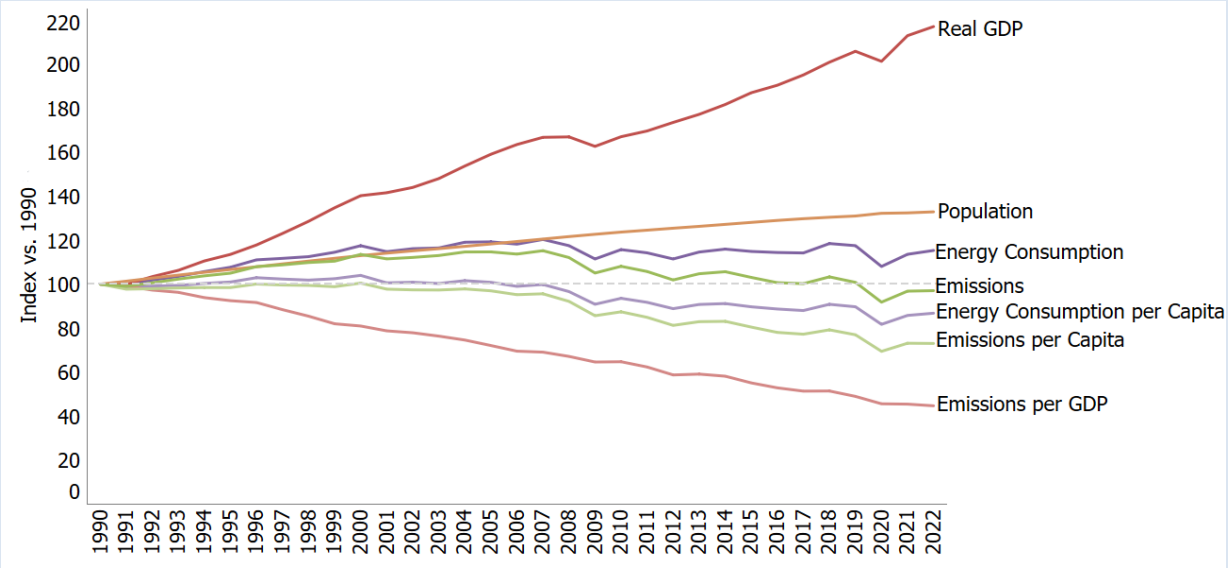
Table 2-14 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.1 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use, overall gross domestic product (GDP) and national population (see Table 2-14 and Figure 2-16). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use and associated fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.9 percent since 2005. Since 2005, GDP, and national population, generally continued to increase, and energy use has decreased slightly, noting 2020 was impacted by the COVID-19 pandemic.

Table 2-14: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2018	2019	2020	2021	2022	Avg. Annual Change Since 1990[a]	Avg. Annual Change Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	103	101	92	97	97	-0.1%	-0.9%
Energy Use[c]	100	119	118	117	107	113	115	0.5%	-0.2%
GDP[d]	100	159	201	206	201	213	217	2.5%	1.9%
Population[e]	100	118	130	131	132	132	133	0.9%	0.7%

[a] Average annual growth rate.
[b] Gross total GWP-weighted values.
[c] Energy-content-weighted values (EIA 2024).
[d] GDP in chained 2017 dollars (BEA 2024).
[e] U.S. Census Bureau (2024).

Figure 2-16: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2024), U.S. Census Bureau (2024), and gross emission estimates in this report.

2.3 Precursor Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the Paris Agreement and the UNFCCC[11] request that information be provided on emissions of compounds that are precursors to greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance, by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Carbon monoxide is produced when carbon-containing fuels are combusted incompletely in energy, transportation, and industrial processes, and is also emitted from practices such as agricultural burning and waste disposal and treatment. Anthropogenic sources of nitrogen oxides (i.e., NO and NO_2) are primarily fossil fuel combustion (for energy, transportation, industrial process) and agricultural burning. Anthropogenic sources of NMVOCs, which include hundreds of organic compounds that participate in atmospheric chemical reactions (propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, oil and natural gas production, waste practices, agricultural burning, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry.

As noted above and summarized in Chapter 6 of IPCC (2021), these compounds can have important indirect effects on Earth's radiative balance. For example, reactions between NMVOCs and NO_x in the presence of sunlight lead to formation of tropospheric ozone, a greenhouse gas. Concentrations of NMVOCs, NO_x, and CO can also impact the abundance and lifetime of primary greenhouse gases. This largely occurs by altering the atmospheric concentrations of the hydroxyl radical (OH), which is the main sink for atmospheric CH_4. For example, NO_x emissions can lead to increases in O_3 concentrations and subsequent OH production, which will increase the amount of OH molecules that are available to destroy CH_4. In contrast, NMVOCs and CO can both react directly with OH, leading to lower OH concentrations, a longer atmospheric lifetime of CH_4, and a decrease in CO_2 production (i.e., CO+OH→ CO_2). Changes in atmospheric CH_4 can also feedback on background concentrations of tropospheric O_3. Other indirect impacts include the formation of sulfate and nitrate aerosol from emissions of NO_x and SO_2, both of which have a net negative impact on radiative forcing.

Since 1970, the United States has published triennial estimates of emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2023a), which are regulated under the Clean Air Act. Emissions of each of these precursor greenhouse gases has decreased significantly since 1990 as a result of implementation of Clean Air Act programs, as well as technological improvements.[12] Precursor emission estimates for this report for 1990 through 2022 were obtained from data published on EPA's National Emissions Inventory (NEI) Air Pollutants Emissions Trends Data website (EPA 2023a). For Table 2-15, NEI-reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Emissions Inventory System (EIS) source categories to those more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on the crosswalk detailed in Annex 6.3. Table 2-15 shows that fuel combustion accounts for the majority of emissions of these precursors. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs. Precursor emissions from Agriculture and LULUCF categories are estimated separately and therefore are not taken from EPA (2023a).

[11] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[12] More information is available online at: https://www.epa.gov/clean-air-act-overview/progress-cleaning-air-and-improving-peoples-health and https://gispub.epa.gov/neireport/2017/.

Table 2-15: Emissions of NO_x, CO, NMVOCs, and SO_2 (kt)

Gas/Activity	1990	2005	2018	2019	2020	2021	2022
NO_x	**22,896**	**19,754**	**8,064**	**7,639**	**6,879**	**6,996**	**6,589**
Energy	21,966	18,863	7,384	7,048	6,235	6,308	5,964
IPPU	774	672	461	440	393	403	389
Agriculture	16	18	17	18	17	18	19
LULUCF	56	149	130	61	158	190	142
Waste	84	51	73	73	76	76	75
CO	**133,549**	**76,691**	**38,656**	**36,234**	**38,911**	**41,677**	**38,853**
Energy	124,713	64,455	30,760	30,349	28,427	28,845	28,173
IPPU	4,099	1,701	1,022	1,011	855	902	897
Agriculture	407	480	433	468	446	480	501
LULUCF	3,301	8,877	5,259	3,224	7,841	10,107	7,939
Waste	1,028	1,178	1,182	1,182	1,342	1,343	1,343
NMVOCs	**20,918**	**12,708**	**8,987**	**8,804**	**9,040**	**9,454**	**9,325**
Energy	13,067	8,694	5,506	5,444	5,306	5,568	5,442
IPPU	6,982	3,668	3,119	2,996	3,366	3,508	3,505
Agriculture	+	194	206	208	196	206	206
LULUCF	NA	NA	NA	NA	NA	NA	NA
Waste	870	152	156	157	173	172	172
SO_2	**20,924**	**13,108**	**2,001**	**1,676**	**1,471**	**1,621**	**1,522**
Energy	19,400	12,312	1,643	1,344	1,173	1,315	1,229
IPPU	1,488	776	335	309	266	274	261
Agriculture	+	0	0	0	+	+	+
LULUCF	NA	NA	NA	NA	NA	NA	NA
Waste	36	20	23	23	33	32	31

+ Does not exceed 0.5 kt.

NA (Not Available)

Note: Totals by gas may not sum due to independent rounding.

Source: (EPA 2023a) except for estimates from forest fires, grassland fires, and field burning of agricultural residues. Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 82.0 percent of total gross greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis in 2022.[1] This included 96.5, 40.2, and 10.8 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively.[2] Energy-related CO_2 emissions alone constituted 76.9 percent of total gross U.S. greenhouse gas emissions from all sources on a CO_2-equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total gross national emissions (5.1 percent collectively).

Emissions from fossil fuel combustion contribute the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1 and Figure 3-2). Globally, approximately 33,500 million metric tons (MMT) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2022, of which the United States accounted for approximately 14 percent.[3] Due to their relative importance over time (see Figure 3-2), fossil fuel combustion-related CO_2 emissions are considered in more detail than other energy-related emissions in this report (see Figure 3-3).

Fossil fuel combustion also emits CH_4 and N_2O. Stationary combustion of fossil fuels was the second largest source of N_2O emissions in the United States and mobile fossil fuel combustion was the fifth largest source. Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 emissions from natural gas systems, coal mining, and petroleum systems.

[1] Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

[2] The contribution of energy non-CO_2 emissions is based on gross totals so excludes LULUCF methane (CH_4) and nitrous oxide (N_2O) emissions. The contribution of energy-related methane (CH_4) and (N_2O) including LULUCF non-CO_2 emissions, is 37.1 percent and 9.8 percent respectively.

[3] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Global energy-related CO_2 emissions, 2022.* Available at: https://www.iea.org/reports/co2-emissions-in-2022 (IEA 2022).

Figure 3-1: 2022 Energy Sector Greenhouse Gas Sources

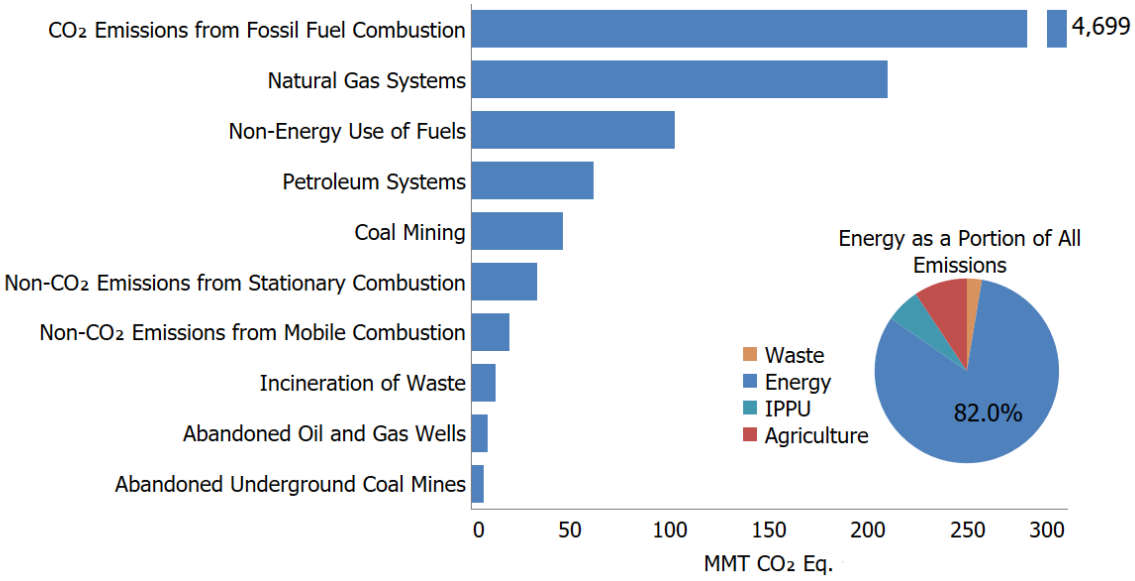


Figure 3-2: Trends in Energy Sector Greenhouse Gas Sources

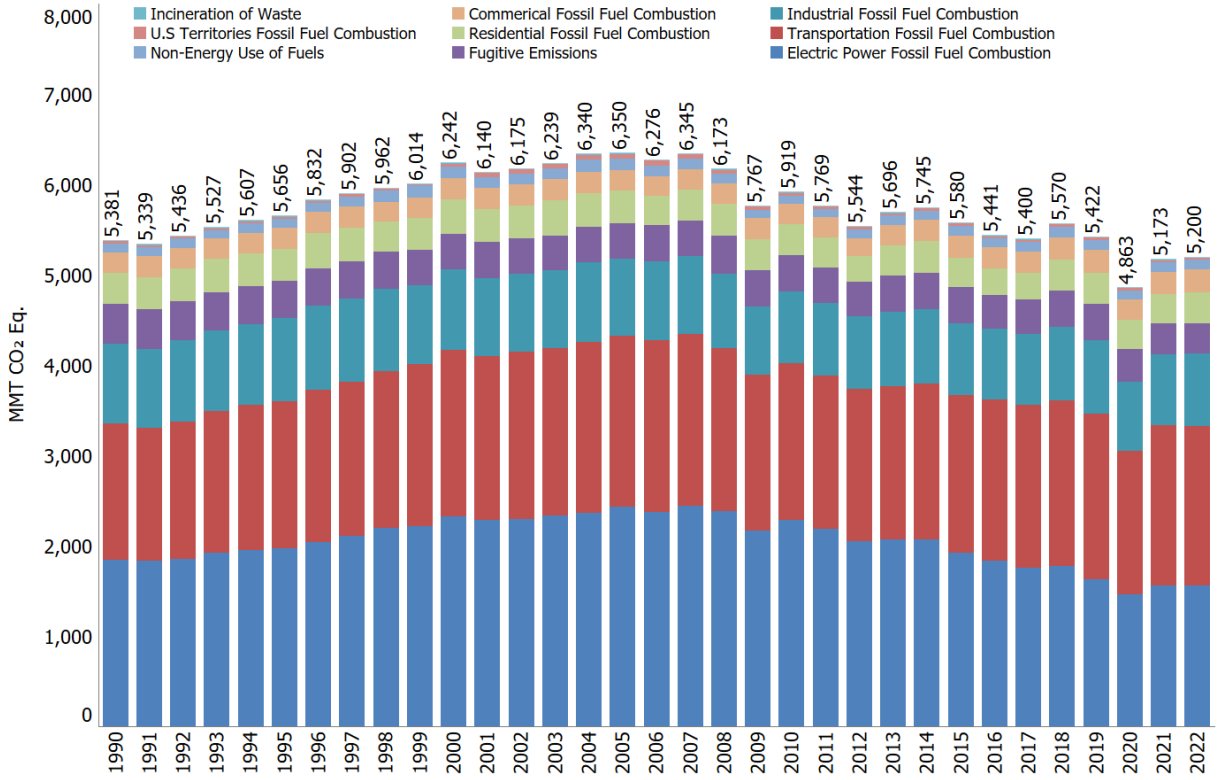


Figure 3-3: 2022 U.S. Fossil Carbon Flows (MMT CO_2 Eq.)

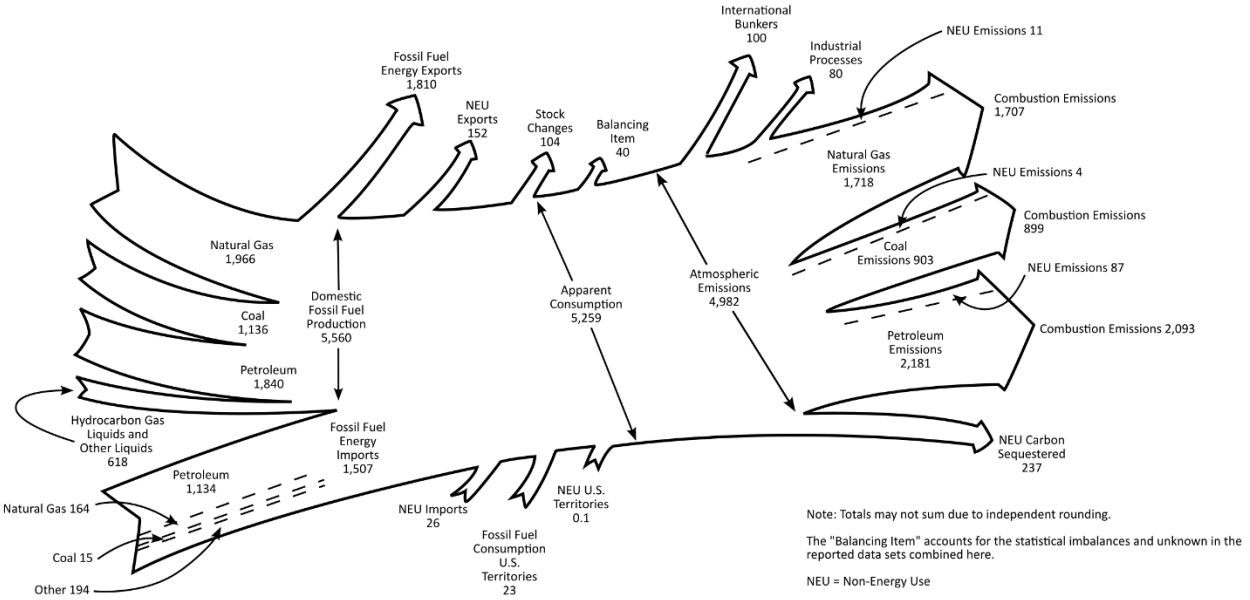


Table 3-1 summarizes emissions from the Energy sector in units of MMT CO_2 Eq., while unweighted gas emissions in kilotons (kt) are provided in Table 3-2. Overall, emissions due to energy-related activities were 5,199.8 MMT CO_2 Eq. in 2022,[4] a decrease of 3.4 percent since 1990 and an increase of 0.5 percent since 2021. The increase in emissions in 2021 and 2022 was due to continued rebounding activity levels after the coronavirus (COVID-19) pandemic reduced overall demand for fossil fuels across all sectors in 2020. Longer term trends are driven by a number of factors including a shift from coal to natural gas and renewables in the electric power sector.

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**4,910.9**	**5,923.1**	**5,190.6**	**5,059.1**	**4,520.2**	**4,840.7**	**4,875.5**
Fossil Fuel Combustion	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
Transportation	*1,468.9*	*1,858.6*	*1,813.1*	*1,816.6*	*1,572.8*	*1,753.5*	*1,751.3*
Electricity Generation	*1,820.0*	*2,400.1*	*1,753.4*	*1,606.7*	*1,439.6*	*1,540.9*	*1,531.7*
Industrial	*876.5*	*847.6*	*810.5*	*809.8*	*762.0*	*780.5*	*801.1*
Residential	*338.6*	*358.9*	*338.9*	*342.9*	*314.8*	*318.0*	*334.1*
Commercial	*228.3*	*227.1*	*246.3*	*251.7*	*229.3*	*237.5*	*258.7*
U.S. Territories	*20.0*	*51.9*	*25.9*	*24.8*	*23.3*	*23.8*	*22.6*
Non-Energy Use of Fuels	99.1	125.0	118.4	106.5	97.8	111.6	102.8
Natural Gas Systems	32.4	26.3	32.8	38.5	36.7	35.8	36.5
Petroleum Systems	9.6	10.2	34.8	45.5	28.9	24.1	22.0
Incineration of Waste	12.9	13.3	13.3	12.9	12.9	12.5	12.4
Coal Mining	4.6	4.2	3.1	3.0	2.2	2.5	2.5
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*220.0*	*217.7*	*190.6*	*192.5*	*195.3*
International Bunker Fuels[b]	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*81.9*	*82.6*	*71.8*	*79.1*	*79.6*

[4] Following the current reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the IPCC *Fifth Assessment Report* (AR5) GWP values. See Chapter 1, Introduction for more information.

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*
Biomass-MSW[a]	*18.5*	*14.7*	*16.1*	*15.7*	*15.6*	*15.3*	*14.9*
CH_4	**409.0**	**358.5**	**336.2**	**321.7**	**305.3**	**293.3**	**282.4**
Natural Gas Systems	218.8	210.1	190.3	188.7	180.3	174.6	173.1
Coal Mining	108.1	71.5	59.1	53.0	46.2	44.7	43.6
Petroleum Systems	49.4	48.2	59.0	52.2	53.3	48.6	39.6
Stationary Combustion	9.7	8.8	9.6	9.8	8.0	8.0	8.6
Abandoned Oil and Gas Wells	7.8	8.2	8.4	8.5	8.5	8.6	8.5
Abandoned Underground Coal Mines	8.1	7.4	6.9	6.6	6.5	6.3	6.3
Mobile Combustion	7.2	4.3	2.8	2.9	2.5	2.6	2.6
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**61.2**	**67.9**	**43.2**	**41.6**	**37.1**	**39.2**	**41.9**
Stationary Combustion	22.3	30.5	25.1	22.2	20.5	22.0	24.7
Mobile Combustion	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Incineration of Waste	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Natural Gas Systems	+	+	+	+	+	+	0.2
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.8*	*0.9*	*1.0*	*0.9*	*0.5*	*0.6*	*0.8*
Total	**5,381.0**	**6,349.5**	**5,570.0**	**5,422.4**	**4,862.6**	**5,173.3**	**5,199.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from biomass and biofuel consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and Paris Agreement and UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

Table 3-2: CO_2, CH_4, and N_2O Emissions from Energy (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**4,910,861**	**5,923,075**	**5,190,611**	**5,059,075**	**4,520,249**	**4,840,748**	**4,875,487**
Fossil Fuel Combustion	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
Non-Energy Use of Fuels	99,104	124,988	118,382	106,474	97,757	111,624	102,808
Natural Gas Systems	32,427	26,312	32,768	38,525	36,719	35,780	36,470
Petroleum Systems	9,585	10,210	34,777	45,498	28,937	24,140	21,967
Incineration of Waste	12,900	13,254	13,339	12,948	12,921	12,476	12,357
Coal Mining	4,606	4,169	3,139	2,992	2,197	2,455	2,474
Abandoned Oil and Gas Wells	7	7	8	8	8	8	8
Biomass-Wood[a]	*215,186*	*206,901*	*220,003*	*217,690*	*190,554*	*192,509*	*195,338*
International Bunker Fuels[b]	*103,634*	*113,328*	*124,279*	*113,632*	*69,638*	*80,180*	*98,241*
Biofuels-Ethanol[a]	*4,227*	*22,943*	*81,917*	*82,578*	*71,848*	*79,064*	*79,593*
Biofuels-Biodiesel[a]	*0*	*856*	*17,936*	*17,080*	*17,678*	*16,112*	*15,622*
Biomass-MSW[a]	*18,534*	*14,722*	*16,115*	*15,709*	*15,614*	*15,329*	*14,864*
CH_4	**14,607**	**12,804**	**12,007**	**11,490**	**10,903**	**10,476**	**10,084**
Natural Gas Systems	7,813	7,505	6,795	6,741	6,439	6,235	6,183
Coal Mining	3,860	2,552	2,110	1,892	1,648	1,595	1,558
Petroleum Systems	1,765	1,723	2,108	1,865	1,904	1,737	1,415
Stationary Combustion	345	313	344	351	285	286	307
Abandoned Oil and Gas Wells	279	294	301	302	303	306	303
Abandoned Underground Coal Mines	288	264	247	237	232	224	225
Mobile Combustion	258	154	101	102	91	92	93
Incineration of Waste	+	+	+	+	+	+	+

Gas/Source	1990	2005	2018	2019	2020	2021	2022
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*3*	*3*	*3*
N_2O	**231**	**256**	**163**	**157**	**140**	**148**	**158**
Stationary Combustion	84	115	95	84	78	83	93
Mobile Combustion	145	140	67	72	61	63	63
Incineration of Waste	2	1	1	1	1	1	1
Natural Gas Systems	+	+	+	+	+	+	0.6
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*4*	*3*	*2*	*2*	*3*

+ Does not exceed 0.5 kt.

[a] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Note: Totals by gas may not sum due to independent rounding.

Emissions estimates reported in the Energy chapter from fossil fuel combustion and fugitive sources include those from all 50 states, including Hawaii and Alaska, and the District of Columbia. Emissions are also included from U.S. Territories to the extent they are known to occur (e.g., coal mining does not occur in U.S. Territories). For some sources there is a lack of detailed information on U.S. Territories including some non-CO_2 emissions from biomass combustion. As part of continuous improvement efforts, EPA reviews this on an ongoing basis to ensure emission sources are included across all geographic areas including U.S. Territories if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Each year, some emission and sink estimates in the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to ensure that the trend is accurate. Key updates in this year's *Inventory* include, updated methodologies for completion and workover emissions estimates and transmission compressor station activity from both natural gas systems and petroleum systems, a shift of all product supplied of natural gasoline and unfinished oils to crude oil transfers for the time series and changes to the non-energy use of fossil fuel methodology (e.g., updates to some of the data and updated methodology for the amount of NEU HGLs). The impact of these recalculations averaged a decrease of 0.2 MMT CO_2 Eq. (less than 0.1 percent) per year across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the Energy chapter do not preclude alternative examinations (e.g., economic sectors). Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from energy-related activities.

Energy Data from EPA's Greenhouse Gas Reporting Program

EPA's Greenhouse Gas Reporting Program (GHGRP)[5] dataset and the data presented in this Inventory are complementary. The *Inventory* was used to guide the development of the GHGRP, particularly in terms of scope and coverage of both sources and gases. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of Energy sector categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines (see Box 3-3 of this chapter, and Sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.7 Natural Gas Systems).[6] Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods. Under EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. It should be noted that the definitions and provisions for reporting fuel types in EPA's GHGRP may differ from those used in the Inventory in meeting the Paris Agreement and UNFCCC reporting guidelines. In line with the Paris Agreement and UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from fuel types identified in the IPCC guidelines and provides a separate reporting of emissions from biomass.

In addition to using GHGRP data to estimate emissions (Sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.7 Natural Gas Systems), EPA also uses the GHGRP fuel consumption activity data in the Energy sector to disaggregate industrial end-use sector emissions in the category of CO_2 emissions from fossil fuel combustion, for use in reporting emissions in Common Reporting Tables (CRTs) (see Box 3-3). The industrial end-use sector activity data collected for the *Inventory* (EIA 2024) represent aggregated data for the industrial end-use sector. EPA's GHGRP collects industrial fuel consumption activity data by individual categories within the industrial end-use sector. Therefore, GHGRP data are used to provide a more detailed breakout of total emissions in the industrial end-use sector within that source category.

As indicated in the respective Planned Improvements sections for source categories in this chapter, EPA continues to examine the uses of facility-level GHGRP data to improve the national estimates presented in this *Inventory*. See Annex 9 for more information on use of EPA's GHGRP in the *Inventory*.

3.1 Fossil Fuel Combustion (CRT Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the greenhouse gases CO_2, CH_4, and N_2O. Given that CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO_2 emissions from fossil fuel combustion are discussed at the beginning of this section. An overview of CH_4 and N_2O emissions from the combustion of fuels in stationary sources is then presented, followed by fossil fuel

[5] On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[6] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

combustion emissions for all three gases by sector: electric power, industrial, residential, commercial, U.S. Territories, and transportation.

Methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of CH_4 and N_2O emissions from stationary combustion and mobile combustion. Thus, three separate descriptions of methodologies, uncertainties, recalculations, and planned improvements are provided at the end of this section. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	4,752.2	5,744.1	4,988.2	4,852.6	4,341.7	4,654.3	4,699.4
CH_4	16.9	13.1	12.5	12.7	10.5	10.6	11.2
N_2O	60.8	67.6	42.8	41.2	36.7	38.9	41.4
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

Note: Totals may not sum due to independent rounding.

Table 3-4: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	4,752,232	5,744,134	4,988,198	4,852,631	4,341,710	4,654,265	4,699,403
CH_4	602	467	445	453	376	379	401
N_2O	229	255	161	156	138	147	156

CO_2 from Fossil Fuel Combustion

Carbon dioxide is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. Carbon dioxide emissions from fossil fuel combustion are presented in Table 3-5. In 2022, CO_2 emissions from fossil fuel combustion increased by 1.0 percent relative to the previous year (as shown in Table 3-6). The increase in CO_2 emissions from fossil fuel combustion was a result of a 1.8 percent increase in fossil fuel energy use. This increase in fossil fuel energy use was due primarily to the continued rebound in economic activity after the COVID-19 pandemic. Carbon dioxide emissions from natural gas increased by 84.8 MMT CO_2 Eq., a 5.2 percent increase from 2021. In a shift from last year's trend, CO_2 emissions from coal consumption decreased by 58.6 MMT CO_2 Eq., a 6.1 percent decrease from 2021. Both the increase in natural gas and decrease in coal consumption and emissions in 2022 are observed across all sectors. Emissions from petroleum use also increased 19.0 MMT CO_2 Eq. (0.9 percent) from 2021 to 2022. In 2022, CO_2 emissions from fossil fuel combustion were 4,699,4 MMT CO_2 Eq., or 1.1 percent below emissions in 1990 (see Table 3-5).[7]

[7] An additional discussion of fossil fuel emission trends is presented in the Trends in U.S. Greenhouse Gas Emissions chapter.

Table 3-5: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq.)

Fuel/Sector	1990	2005	2018	2019	2020	2021	2022
Coal	**1,719.8**	**2,113.7**	**1,211.6**	**1,028.1**	**835.6**	**957.4**	**898.8**
Residential	3.0	0.8	NO	NO	NO	NO	NO
Commercial	12.0	9.3	1.8	1.6	1.4	1.4	1.4
Industrial	157.8	117.8	54.4	49.4	43.0	43.0	43.0
Transportation	NO	NO	NO	NO	NO	NO	NO
Electric Power	1,546.5	1,982.8	1,152.9	973.5	788.2	910.1	851.5
U.S. Territories	0.5	3.0	2.6	3.6	3.1	2.9	2.9
Natural Gas	**998.6**	**1,166.2**	**1,592.0**	**1,649.2**	**1,615.7**	**1,622.1**	**1,706.8**
Residential	237.8	262.2	273.8	275.5	256.4	258.6	272.0
Commercial	142.0	162.9	192.5	192.9	173.5	180.4	192.3
Industrial	407.4	387.8	493.5	501.5	489.7	501.2	510.4
Transportation	36.0	33.1	50.9	58.9	58.7	65.2	70.2
Electric Power	175.4	318.9	577.9	616.6	634.8	612.8	659.3
U.S. Territories	NO	1.3	3.3	3.8	2.6	3.9	2.7
Petroleum	**2,033.3**	**2,463.8**	**2,184.2**	**2,174.9**	**1,890.0**	**2,074.4**	**2,093.4**
Residential	97.8	95.9	65.1	67.4	58.4	59.4	62.1
Commercial	74.3	54.9	52.0	57.2	54.4	55.7	65.1
Industrial	311.2	342.0	262.6	258.9	229.3	236.3	247.6
Transportation	1,432.9	1,825.5	1,762.2	1,757.7	1,514.2	1,688.4	1,681.1
Electric Power	97.5	98.0	22.2	16.2	16.2	17.7	20.5
U.S. Territories	19.5	47.6	20.1	17.5	17.5	17.0	17.0
Geothermal[a]	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Electric Power	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Total	**4,752.2**	**5,744.1**	**4,988.2**	**4,852.6**	**4,341.7**	**4,654.3**	**4,699.4**

NO (Not Occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Note: Totals may not sum due to independent rounding.

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants. The 2021 to 2022 trends reflect ongoing impacts of the COVID-19 pandemic which generally led to a reduction in demand for fossil fuels in 2020, but an increase in demand as activities continued to rebound in 2022.

Longer-term changes in energy usage patterns, however, tend to be more a function of aggregate societal trends that affect the scale of energy use (e.g., population, number of cars, size of houses, and number of houses), the efficiency with which energy is used in equipment (e.g., cars, HVAC systems, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions also depend on the source of energy and its carbon intensity. The amount of carbon in fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about

55 percent.[8] Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 3-6: Annual Change in CO_2 Emissions and Total 2022 CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO_2 Eq. and Percent)

Sector	Fuel Type	2018 to 2019		2019 to 2020		2020 to 2021		2021 to 2022		Total 2022
Transportation	Petroleum	-4.5	-0.3%	-243.5	-13.9%	174.2	11.5%	-7.2	-0.4%	1,681.1
Electric Power	Coal	-179.3	-15.6%	-185.4	-19.0%	121.9	15.5%	-58.6	-6.4%	851.5
Electric Power	Natural Gas	38.7	6.7%	18.2	3.0%	-22.1	-3.5%	46.5	7.6%	659.3
Industrial	Natural Gas	8.0	1.6%	-11.8	-2.4%	11.4	2.3%	9.2	1.8%	510.4
Residential	Natural Gas	1.7	0.6%	-19.1	-6.9%	2.3	0.9%	13.3	5.2%	272.0
Commercial	Natural Gas	0.4	0.2%	-19.5	-10.1%	6.9	4.0%	11.9	6.6%	192.3
Transportation	**All Fuels[a]**	**3.5**	**0.2%**	**-243.8**	**-13.4%**	**180.7**	**11.5%**	**-2.3**	**-0.1%**	**1,751.3**
Electric Power	**All Fuels[a]**	**-146.7**	**-8.4%**	**-167.2**	**-10.4%**	**101.4**	**7.0%**	**-9.3**	**-0.6%**	**1,531.7**
Industrial	**All Fuels[a]**	**-0.7**	**-0.1%**	**-47.8**	**-5.9%**	**18.5**	**2.4%**	**20.6**	**2.6%**	**801.1**
Residential	**All Fuels[a]**	**4.0**	**1.2%**	**-28.1**	**-8.2%**	**3.2**	**1.0%**	**16.0**	**5.0%**	**334.1**
Commercial	**All Fuels[a]**	**5.5**	**2.2%**	**-22.5**	**-8.9%**	**8.3**	**3.6%**	**21.2**	**8.9%**	**258.7**
All Sectors[a,b]	**All Fuels[a]**	**-135.6**	**-2.7%**	**-510.9**	**-10.5%**	**312.6**	**7.2%**	**45.1**	**1.0%**	**4,699.4**

[a] Includes sector and fuel combinations not shown in this table.

[b] Includes U.S. Territories.

Note: Totals may not sum due to independent rounding.

As shown in Table 3-6, recent trends in CO_2 emissions from fossil fuel combustion show a 2.7 percent decrease from 2018 to 2019, a 10.5 percent decrease from 2019 to 2020, a 7.2 percent increase from 2020 to 2021, and a 1.0 percent increase from 2021 to 2022. These changes contributed to an overall 5.8 percent decrease in CO_2 emissions from fossil fuel combustion from 2018 to 2022.

The overall 2021 to 2022 trends were largely driven by the gradual recovery from the COVID-19 pandemic, which saw reduced economic activity in 2020 and caused changes in energy demand and supply patterns across different sectors. The continued recovery from the COVID-19 pandemic has generally led to increased energy use and emissions across all economic sectors except electric power and transportation from 2021 to 2022. The decrease in emissions from 2021 to 2022 from electric power was due to the reduction in coal consumption for electricity generation, in a return to a pre-pandemic trend in declining coal-fired power generation.

Recent trends in CO_2 emissions from fossil fuel combustion are largely driven by the electric power sector, which until 2017 has accounted for the largest portion of these emissions. The types of fuels consumed to produce electricity have changed in recent years. Electric power sector consumption of natural gas primarily increased due to increased production capacity as natural gas-fired plants replaced coal-fired plants and increased electricity demand related to heating and cooling needs (EIA 2018; EIA 2023a). Total net electric power generation from all fossil and non-fossil sources decreased by 1.3 percent from 2018 to 2019, decreased by 2.9 percent from 2019 to 2020, increased by 2.7 percent from 2020 to 2021, and increased by 3.0 percent from 2021 to 2022 (EIA 2024a). Carbon dioxide emissions from the electric power sector decreased from 2021 to 2022 by 0.6 percent due to increased production and use of natural gas and decreased production and use of coal for electric power generation. Carbon dioxide emissions from coal consumption for electric power generation decreased by 26.1 percent overall since 2018, including a 6.4 percent decrease from 2021 to 2022.

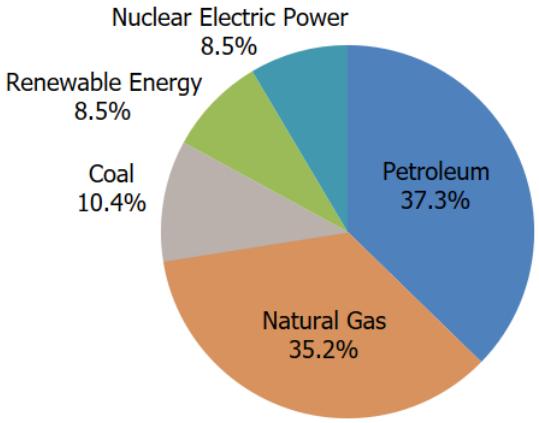
Petroleum use in the transportation sector is another major driver of emissions, representing the largest source of CO_2 emissions from fossil fuel combustion in 2022. Emissions from petroleum consumption for transportation have decreased by 4.6 percent since 2018 and are primarily attributed to a 1.4 percent decrease in VMT over the same

[8] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States. See Annex 2.2 for more details on fuel carbon contents.

time period. As of 2017, the transportation sector is the largest source of national CO_2 emissions–whereas in prior years, electric power was the largest source sector.

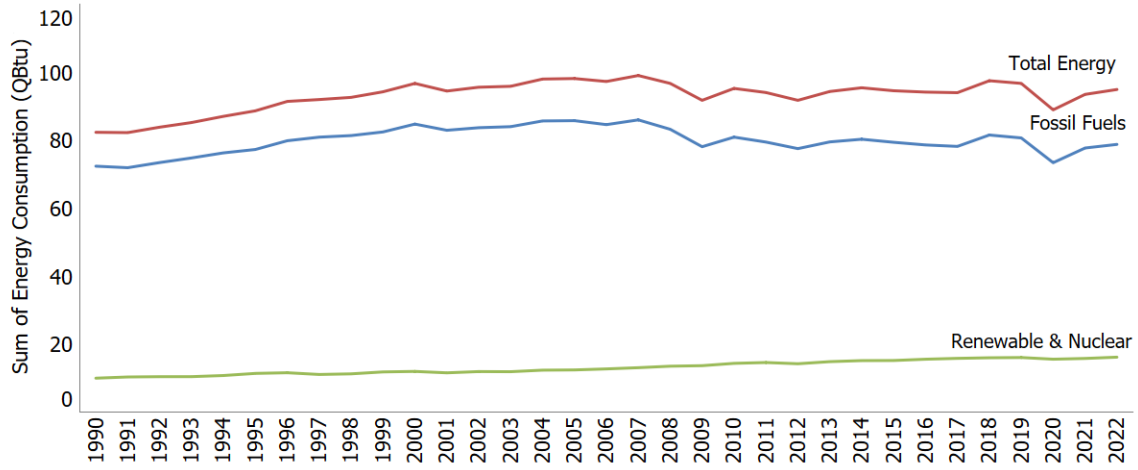
In the United States, 83.0 percent of the energy used in 2022 was produced through the combustion of fossil fuels such as petroleum, natural gas, and coal (see Figure 3-4 and Figure 3-5). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 37 percent of total U.S. energy used in 2022. Natural gas and coal followed in order of fossil fuel energy demand significance, accounting for approximately 35 percent and 10 percent of total U.S. energy used, respectively. Petroleum was consumed primarily in the transportation end-use sector and the majority of coal was used in the electric power sector. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-6) (EIA 2024a). The remaining portion of energy used in 2022 was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (9 percent), primarily wind energy, hydroelectric power, solar, geothermal and biomass (EIA 2024a).[9]

Figure 3-4: 2022 U.S. Energy Use by Energy Source



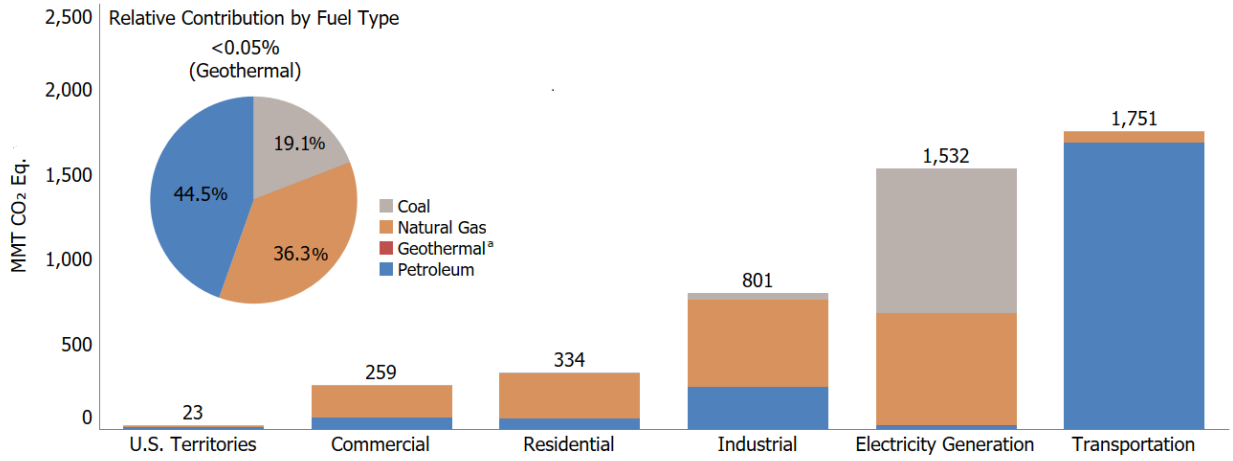
Note: Totals may not sum due to independent rounding.

Figure 3-5: Annual U.S. Energy Use



[9] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biomass, solar energy, and wind energy.

Figure 3-6: 2022 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the carbon stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[10] These other C-containing non-CO_2 gases are emitted as a byproduct of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, as per IPCC guidelines, it is assumed that all of the carbon in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

Box 3-2: Weather and Non-Fossil Energy Effects on CO_2 Emissions from Fossil Fuel Combustion Trends

The United States in 2022 experienced a colder winter overall compared to 2021, with a 7.9 percent increase in heating degree days, although 2022 heating degree days were 2.3 percent below normal (see Figure 3-7). Along with a colder winter, 2022 experienced a warmer summer, with cooling degree days 16.9 percent above normal and 4.3 percent higher compared to 2021 (see Figure 3-8) (EIA 2024a).[11] Warmer summers and colder winters can lead to increased energy use to heat and cool building spaces in the residential and commercial sectors. The combination of colder winter and warmer summer conditions in 2022 as compared to 2021 led to an overall increase in direct emissions from fossil fuel combustion in the residential and commercial sectors of 5.0 and 8.9 percent, respectively.

[10] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

[11] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 degrees Fahrenheit, while cooling degree days are deviations of the mean daily temperature above 65 degrees Fahrenheit. Heating degree days have a considerably greater effect on energy demand and related emissions than do cooling degree days. Excludes Alaska and Hawaii. Normals are based on data from 1991 through 2020. The variation in these normals during this time period was ±16 percent and ±27 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure 3-7: Annual Deviations from Normal Heating Degree Days for the United States (1970–2022, Index Normal = 100)

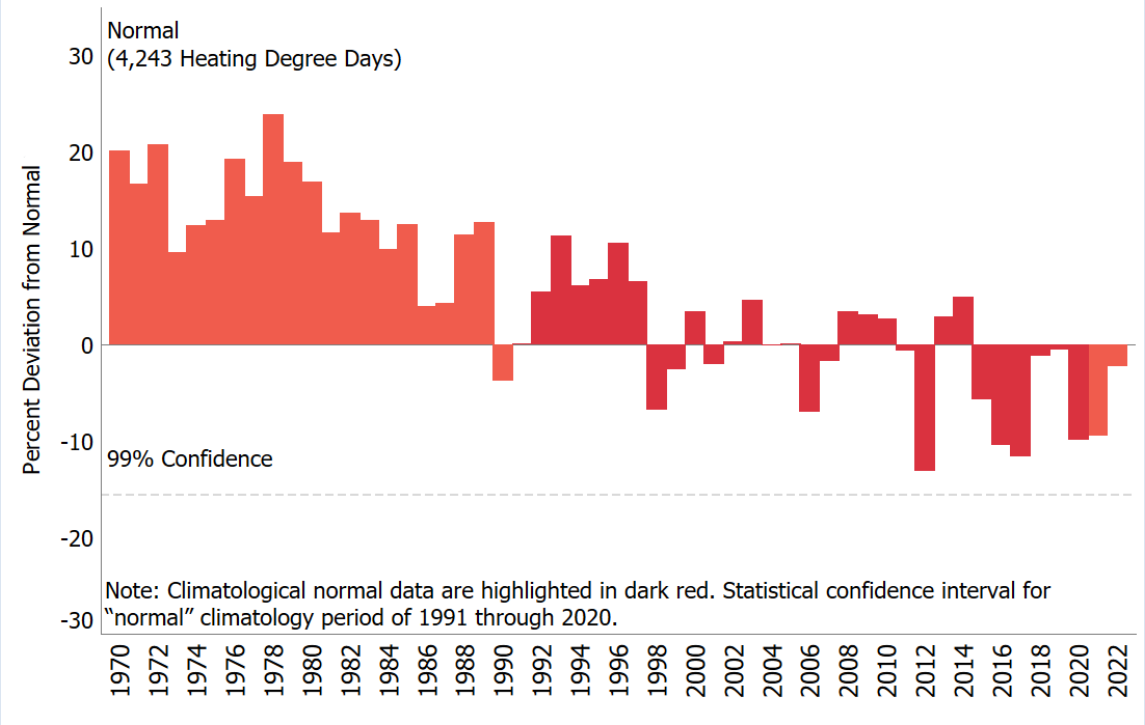
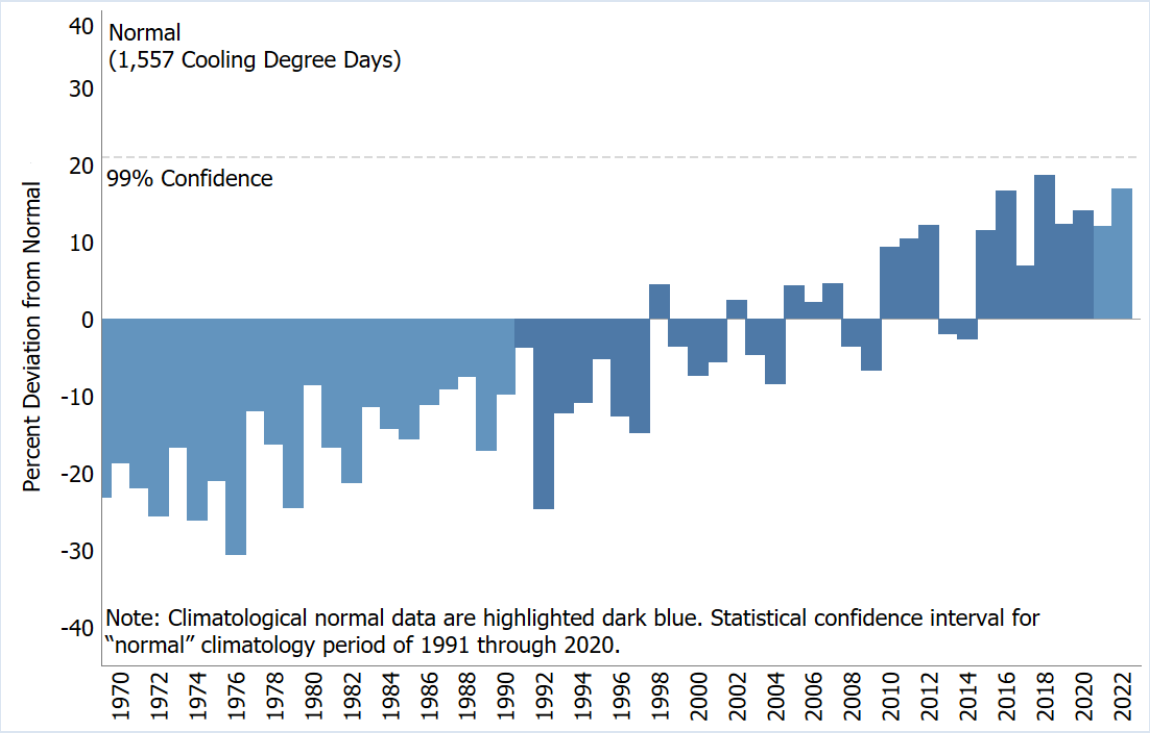


Figure 3-8: Annual Deviations from Normal Cooling Degree Days for the United States (1970–2022, Index Normal = 100)



The carbon intensity of the electric power sector is impacted by the amount of non-fossil energy sources of electricity. The utilization (i.e., capacity factors)[12] of nuclear power plants in 2022 remained high at 93 percent. In 2022, nuclear power represented 19 percent of total electricity generation. Since 1990, the wind and solar power sectors have shown strong growth and have become relatively important sources of electricity. Between 1990 and 2022, renewable energy generation (in kWh) from solar and wind energy have increased from 0.1 percent in 1990 to 14 percent of total electricity generation in 2022, which helped drive the decrease in the carbon intensity of the electricity supply in the United States.

Stationary Combustion

The direct combustion of fuels by stationary sources in the electric power, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-7 presents CO_2 emissions from fossil fuel combustion by stationary sources. The CO_2 emitted is closely linked to the type of fuel being combusted in each sector (see the Methodology section of CO_2 from Fossil Fuel Combustion). In addition to CO_2 emissions, CH_4 and N_2O are emitted from fossil fuel combustion as well. Table 3-8 and Table 3-9 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources. The CH_4 and N_2O emissions are linked to the type of fuel being combusted as well as the combustion technology (see the Methodology section for CH_4 and N_2O from Stationary Combustion).

Table 3-7: CO_2 Emissions from Stationary Fossil Fuel Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**1,820.0**	**2,400.1**	**1,753.4**	**1,606.7**	**1,439.6**	**1,540.9**	**1,531.7**
Coal	1,546.5	1,982.8	1,152.9	973.5	788.2	910.1	851.5
Natural Gas	175.4	318.9	577.9	616.6	634.8	612.8	659.3
Fuel Oil	97.5	98.0	22.2	16.2	16.2	17.7	20.5
Geothermal	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Industrial	**876.5**	**847.6**	**810.5**	**809.8**	**762.0**	**780.5**	**801.1**
Coal	157.8	117.8	54.4	49.4	43.0	43.0	43.0
Natural Gas	407.4	387.8	493.5	501.5	489.7	501.2	510.4
Fuel Oil	311.2	342.0	262.6	258.9	229.3	236.3	247.6
Residential	**338.6**	**358.9**	**338.9**	**342.9**	**314.8**	**318.0**	**334.1**
Coal	3.0	0.8	NO	NO	NO	NO	NO
Natural Gas	237.8	262.2	273.8	275.5	256.4	258.6	272.0
Fuel Oil	97.8	95.9	65.1	67.4	58.4	59.4	62.1
Commercial	**228.3**	**227.1**	**246.3**	**251.7**	**229.3**	**237.5**	**258.7**
Coal	12.0	9.3	1.8	1.6	1.4	1.4	1.4
Natural Gas	142.0	162.9	192.5	192.9	173.5	180.4	192.3
Fuel Oil	74.3	54.9	52.0	57.2	54.4	55.7	65.1
U.S. Territories	**20.0**	**51.9**	**25.9**	**24.8**	**23.3**	**23.8**	**22.6**
Coal	0.5	3.0	2.6	3.6	3.1	2.9	2.9
Natural Gas	NO	1.3	3.3	3.8	2.6	3.9	2.7
Fuel Oil	19.5	47.6	20.1	17.5	17.5	17.0	17.0
Total	**3,283.3**	**3,885.6**	**3,175.1**	**3,036.0**	**2,768.9**	**2,900.7**	**2,948.1**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

[12] The capacity factor equals generation divided by net summer capacity. Summer capacity is defined as "The maximum output that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)" (EIA 2020a). Data for both the generation and net summer capacity are from EIA (2024a).

Table 3-8: CH_4 Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**0.5**	**1.0**	**1.4**	**1.4**	**1.4**	**1.4**	**1.3**
Coal	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.5	1.1	1.2	1.2	1.2	1.0
Wood	+	+	+	+	+	+	+
Industrial	**2.1**	**1.9**	**1.7**	**1.7**	**1.6**	**1.6**	**1.6**
Coal	0.5	0.3	0.2	0.1	0.1	0.1	0.1
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.1	0.2
Natural gas	0.2	0.2	0.2	0.3	0.2	0.3	0.3
Wood	1.2	1.2	1.1	1.1	1.1	1.1	1.0
Commercial	**1.2**	**1.2**	**1.4**	**1.4**	**1.3**	**1.3**	**1.4**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.2	0.2	0.2	0.2	0.3
Natural gas	0.4	0.4	0.5	0.5	0.4	0.5	0.5
Wood	0.5	0.6	0.7	0.7	0.7	0.7	0.7
Residential	**5.9**	**4.5**	**5.1**	**5.3**	**3.6**	**3.6**	**4.3**
Coal	0.3	0.1	NO	NO	NO	NO	NO
Fuel Oil	0.4	0.4	0.3	0.3	0.2	0.2	0.3
Natural Gas	0.6	0.7	0.7	0.7	0.6	0.6	0.7
Wood	4.6	3.4	4.2	4.4	2.8	2.7	3.4
U.S. Territories	**+**	**0.1**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**9.7**	**8.8**	**9.6**	**9.8**	**8.0**	**8.0**	**8.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-9: N_2O Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2018	2019	2020	2021	2022
Electric Power	**18.2**	**26.7**	**21.7**	**18.8**	**17.5**	**19.0**	**21.6**
Coal	17.9	24.9	18.1	14.8	13.5	15.1	18.2
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	0.3	1.7	3.6	3.9	4.0	3.9	3.4
Wood	+	+	+	+	+	+	+
Industrial	**2.8**	**2.6**	**2.2**	**2.2**	**2.0**	**2.1**	**2.0**
Coal	0.7	0.5	0.2	0.2	0.2	0.2	0.2
Fuel Oil	0.5	0.5	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.5	1.5	1.4	1.4	1.4	1.4	1.3
Commercial	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**0.9**	**0.8**	**0.8**	**0.8**	**0.6**	**0.6**	**0.7**
Coal	+	+	NO	NO	NO	NO	NO
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.1	0.1

Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.6	0.4	0.5	0.5	0.3	0.3	0.4
U.S. Territories	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**22.3**	**30.5**	**25.1**	**22.2**	**20.5**	**22.0**	**24.7**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

Fossil Fuel Combustion Emissions by Sector

Table 3-10 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector, including transportation, electric power, industrial, residential, commercial, and U.S. Territories.

Table 3-10: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,514.6**	**1,899.9**	**1,833.6**	**1,838.6**	**1,591.5**	**1,772.9**	**1,770.6**
CO_2	1,468.9	1,858.6	1,813.1	1,816.6	1,572.8	1,753.5	1,751.3
CH_4	7.2	4.3	2.8	2.9	2.5	2.6	2.6
N_2O	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Electric Power	**1,838.7**	**2,427.8**	**1,776.5**	**1,626.9**	**1,458.5**	**1,561.3**	**1,554.5**
CO_2	1,820.0	2,400.1	1,753.4	1,606.7	1,439.6	1,540.9	1,531.7
CH_4	0.5	1.0	1.4	1.4	1.4	1.4	1.3
N_2O	18.2	26.7	21.7	18.8	17.5	19.0	21.6
Industrial	**881.3**	**852.2**	**814.4**	**813.7**	**765.6**	**784.1**	**804.7**
CO_2	876.5	847.6	810.5	809.8	762.0	780.5	801.1
CH_4	2.1	1.9	1.7	1.7	1.6	1.6	1.6
N_2O	2.8	2.6	2.2	2.2	2.0	2.1	2.0
Residential	**345.4**	**364.2**	**344.9**	**349.1**	**319.0**	**322.3**	**339.1**
CO_2	338.6	358.9	338.9	342.9	314.8	318.0	334.1
CH_4	5.9	4.5	5.1	5.3	3.6	3.6	4.3
N_2O	0.9	0.8	0.8	0.8	0.6	0.6	0.7
Commercial	**229.8**	**228.6**	**248.0**	**253.5**	**230.9**	**239.2**	**260.5**
CO_2	228.3	227.1	246.3	251.7	229.3	237.5	258.7
CH_4	1.2	1.2	1.4	1.4	1.3	1.3	1.4
N_2O	0.3	0.3	0.3	0.3	0.3	0.3	0.3
U.S. Territories[a]	**20.1**	**52.1**	**26.0**	**24.9**	**23.4**	**23.9**	**22.7**
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

[a] U.S. Territories are not apportioned by sector, and emissions shown in the table are total greenhouse gas emissions from all fuel combustion sources.
Note: Totals may not sum due to independent rounding.

Other than the greenhouse gases CO_2, CH_4, and N_2O, gases emitted from stationary combustion include the greenhouse gas precursors nitrogen oxides (NO_x), CO, NMVOCs, and sulfur dioxide (SO_2). Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics and the size and vintage of combustion device, along with combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. Nitrous oxide emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Methane emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.

Mobile combustion also produces emissions of CH_4, N_2O, and greenhouse gas precursors including NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions from mobile combustion are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. Nitrous oxide from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in vehicle idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions (such as catalytic converters).

An alternative method of presenting combustion emissions is to allocate emissions associated with electric power to the sectors in which it is used. Four end-use sectors are defined: transportation, industrial, residential, and commercial. In Table 3-11 below, electric power emissions have been distributed to each end-use sector based upon the sector's share of national electricity use, with the exception of CH_4 and N_2O from transportation electricity use.[13] Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data.[14] This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity use in that sector. The results of this alternative method are presented in Table 3-11.

Table 3-11: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector with Electricity Emissions Distributed (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	**1,517.6**	**1,904.6**	**1,838.4**	**1,843.4**	**1,595.6**	**1,778.0**	**1,776.7**
CO_2	1,472.0	1,863.3	1,817.9	1,821.4	1,576.9	1,758.6	1,757.4
CH_4	7.2	4.3	2.8	2.9	2.5	2.6	2.6
N_2O	38.4	37.0	17.7	19.1	16.1	16.8	16.7
Industrial	**1,574.8**	**1,597.0**	**1,322.4**	**1,285.0**	**1,180.8**	**1,235.2**	**1,248.2**
CO_2	1,562.9	1,584.0	1,311.8	1,275.3	1,171.8	1,225.6	1,238.0
CH_4	2.2	2.2	2.1	2.1	2.0	2.0	1.9
N_2O	9.7	10.8	8.5	7.6	7.1	7.6	8.2
Residential	**944.2**	**1,230.1**	**995.7**	**940.2**	**871.6**	**902.1**	**912.9**
CO_2	931.3	1,214.9	981.2	926.7	860.1	890.3	899.4
CH_4	6.0	4.9	5.6	5.8	4.2	4.2	4.8
N_2O	6.9	10.3	8.8	7.7	7.3	7.7	8.7
Commercial	**773.1**	**1,040.9**	**861.0**	**813.1**	**717.6**	**764.6**	**791.6**
CO_2	766.0	1,030.1	851.3	804.4	709.6	756.1	782.0
CH_4	1.3	1.5	1.8	1.9	1.8	1.8	1.8
N_2O	5.7	9.3	7.8	6.8	6.2	6.7	7.7
U.S. Territories[a]	**20.1**	**52.1**	**26.0**	**24.9**	**23.4**	**23.9**	**22.7**
Total	**4,829.9**	**5,824.8**	**5,043.4**	**4,906.6**	**4,388.9**	**4,703.7**	**4,752.0**

[a] U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity use by each end-use sector.

[13] Separate calculations are performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions is discussed in the Mobile Combustion section.

[14] U.S. Territories (including American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) consumption data obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

Electric Power Sector

The process of generating electricity is the largest stationary source of CO_2 emissions in the United States, representing 30.3 percent of total CO_2 emissions from all CO_2 emissions sources across the United States. Methane and N_2O accounted for a small portion of total greenhouse gas emissions from electric power, representing 0.1 percent and 1.4 percent, respectively. Electric power also accounted for 32.6 percent of CO_2 emissions from fossil fuel combustion in 2022. Methane and N_2O from electric power represented 11.4 and 52.2 percent of total CH_4 and N_2O emissions from fossil fuel combustion in 2022, respectively.

For the underlying energy data used in this chapter, the Energy Information Administration (EIA) places electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. The energy use and emissions associated with the electric power sector are included here. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity. This includes both regulated utilities and non-utilities (e.g., independent power producers, qualifying co-generators, and other small power producers). Energy use and emissions associated with electric generation in the commercial and industrial sectors is reported in those other sectors where the producer of the power indicates that its primary business is something other than the production of electricity.[15]

Total greenhouse gas emissions from the electric power sector have decreased by 15.5 percent since 1990. From 1990 to 2007, electric power sector emissions increased by 33 percent, driven by a significant increase in electricity demand (39 percent) while the carbon intensity of electricity generated showed a modest decline (2.1 percent). From 2008 to 2022, as electricity demand increased by 5.2 percent, electric power sector emissions decreased by 35 percent, driven by a significant drop (25 percent) in the carbon intensity of electricity generated. Overall, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu, decreased by 28 percent from 1990 to 2022 with additional trends detailed in Box 3-4. This decoupling of electric power generation and the resulting CO_2 emissions is shown in Figure 3-9. This recent decarbonization of the electric power sector is a result of several key drivers.

Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54 percent of generation in 1990 to 20 percent in 2022.[16] This corresponded with an increase in natural gas generation and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 11 percent of electric power generation in 1990 and increased over the 33-year period to represent 39 percent of electric power sector generation in 2022 (see Table 3-12). Natural gas has a much lower carbon content than coal and is generated in power plants that are generally more efficient in terms of kWh produced per Btu of fuel combusted, which has led to lower emissions as natural gas replaces coal-powered electricity generation. Natural gas and coal used in the United States in 2022 had an average carbon content of 14.43 MMT C/Qbtu and 26.13 MMT C/Qbtu respectively.

[15] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Non-utilities typically generate electricity for sale on the wholesale electricity market (e.g., to utilities for distribution and resale to retail customers). Where electricity generation occurs outside the EIA-defined electric power sector, it is typically for the entity's own use.

[16] Values represent electricity *net* generation from the electric power sector (EIA 2024a).

Table 3-12: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	2005	2018	2019	2020	2021	2022
Coal	54.1%	51.1%	28.4%	24.2%	19.9%	22.6%	20.3%
Natural Gas	10.7%	17.5%	34.0%	37.3%	39.5%	37.3%	38.8%
Nuclear	19.9%	20.0%	20.1%	20.4%	20.5%	19.7%	18.9%
Renewables	11.3%	8.3%	16.8%	17.6%	19.5%	19.8%	21.4%
Petroleum	4.1%	3.0%	0.6%	0.4%	0.4%	0.5%	0.5%
Other Gases[a]	+	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Net Electricity Generation (Billion kWh)[b]	2,905	3,902	4,020	3,966	3,851	3,955	4,076

+ Does not exceed 0.05 percent.

[a] Other gases include blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

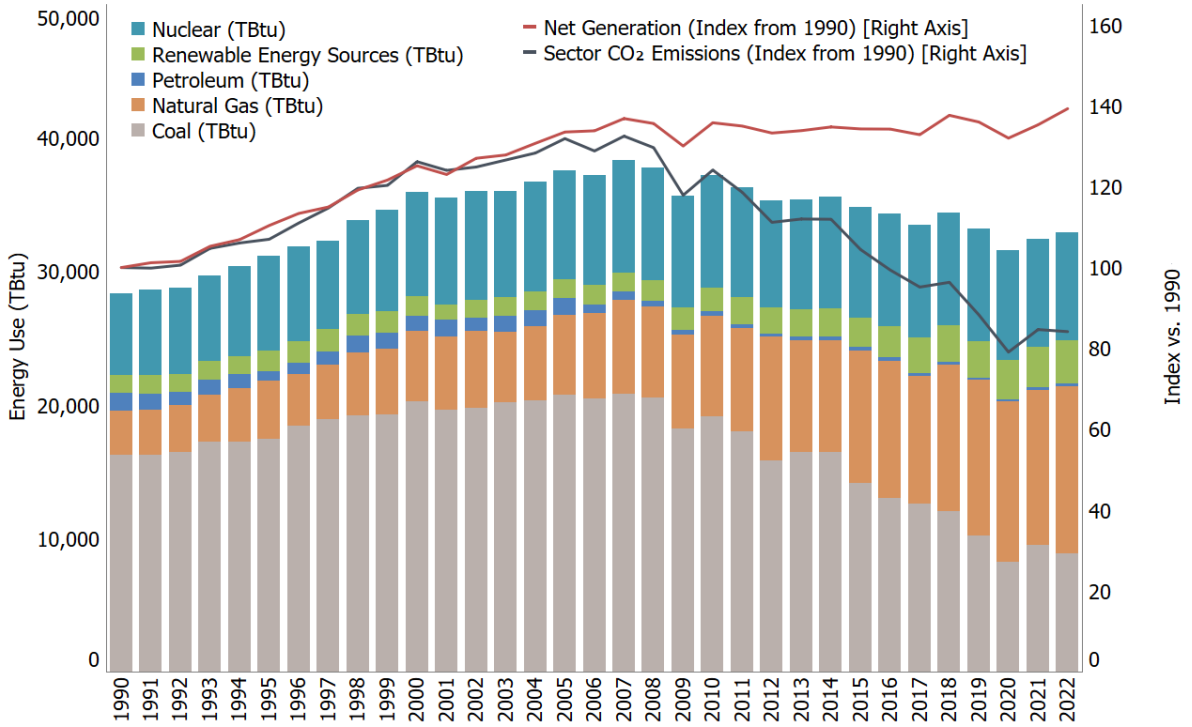
[b] Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined.

In 2022, CO_2 emissions from the electric power sector decreased by 0.6 percent relative to 2021. This decrease in CO_2 emissions was primarily driven by a decrease in coal consumed to produce electricity in the electric power sector. Consumption of coal for electric power decreased by 6.4 percent while consumption of natural gas increased 7.6 percent from 2021 to 2022, leading to an overall decrease in emissions. There has also been a rapid increase in renewable energy electricity generation in the electric power sector in recent years. Electricity generation from renewable sources increased by 11 percent from 2021 to 2022 (see Table 3-12). A decrease in coal-fired electricity generation and increases in natural gas and renewable energy sources for electricity generation contributed to a decoupling of emissions trends from electric power generation trends over the recent time series (see Figure 3-9).

Decreases in natural gas prices and the associated increase in natural gas generation, particularly between 2005 and 2019, was a primary driver of the fuel switching from using coal to using natural gas for electricity generation, which led to a significant decrease in CO_2 emissions from electricity generation. During this time period, the cost of natural gas (in $/MMBtu) decreased by 56 percent while the cost of coal (in $/MMBtu) increased by 74 percent (EIA 2024a). However, from 2020 to 2022, natural gas prices increased 200 percent and are now 9 percent higher than 2005 levels due to the COVID-19 pandemic and other factors disrupting the domestic and global natural gas markets. While the increase in natural gas prices led to a temporary trend reversal, with coal consumption increasing and natural gas consumption decreasing from 2020 to 2021, the broader trend of declining coal consumption for electricity generation continues. From 2021 to 2022, coal consumption decreased 6 percent while natural gas consumption increased 8 percent.

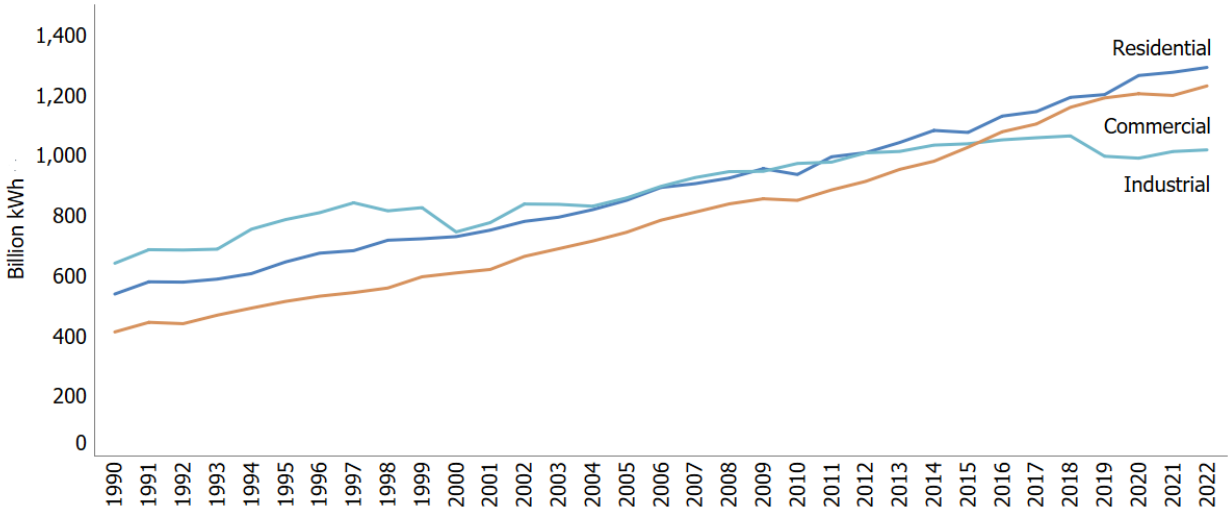
Moving forward, the shift away from coal—and increasingly towards renewable energy sources in addition to natural gas—for electricity generation will further contribute to reductions in power sector emissions. Renewable energy generation (in kWh) from wind and solar energy increased from 0.1 percent of total generation in 1990 to 5 percent in 2015 and increased at a faster pace to 14 percent of total generation in 2022. The decrease in carbon intensity occurred even as total electricity retail sales increased 45 percent, from 2,713 billion kWh in 1990 to 3,927 billion kWh in 2022.

Figure 3-9: Fuels Used in Electric Power Generation and Total Electric Power Sector CO_2 Emissions



Electricity was used primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-10). Note that transportation is an end-use sector as well but is not shown in Figure 3-10 due to the sector's relatively low percentage of electricity use. The Transportation Sector and Mobile Combustion section provides a break-out of CO_2 emissions from electricity use in the transportation end-use sector.

Figure 3-10: Electric Power Retail Sales by End-Use Sector



In 2022, electricity sales to the residential and commercial end-use sectors, as presented in Figure 3-10, increased by 2.6 percent and 4.7 percent relative to 2021, respectively. Electricity sales to the industrial sector in 2022

increased by approximately 2.0 percent relative to 2021. The sections below describe end-use sector energy use in more detail. Overall, in 2022, the amount of electricity retail sales (in kWh) increased by 3.2 percent relative to 2021.

Industrial Sector

Industrial sector CO_2, CH_4, and N_2O emissions accounted for 17, 14, and 5 percent of CO_2, CH_4, and N_2O emissions from fossil fuel combustion, respectively, in 2022. Carbon dioxide, CH_4, and N_2O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial end-use sector, per the underlying energy use data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy use is manufacturing, of which six industries—petroleum refineries, chemicals, paper, primary metals, food, and nonmetallic mineral products—represent the majority of the energy use (EIA 2024a; EIA 2009b).

There are many dynamics that impact emissions from the industrial sector including economic activity, changes in the make-up of the industrial sector, changes in the emissions intensity of industrial processes, and weather-related impacts on heating and cooling of industrial buildings.[17] Structural changes within the U.S. economy that lead to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

From 2021 to 2022, total industrial production and manufacturing output increased by 3.4 percent (FRB 2022). Over this period, output increased slightly across production indices for Food, Nonmetallic Mineral Products, Paper, Petroleum Refineries, and Primary Metals. Production of chemicals declined slightly between 2021 and 2022 (see Figure 3-11). From 2021 to 2022, total energy use in the industrial sector increased by 2.0 percent, driven mainly by a 2.6 percent increase in fossil fuel consumption in the industrial sector. Consumption of renewables decreased 1.6 percent from 2021 to 2022. Due to the relative increases and decreases of individual indices there was an increase in natural gas and an increase in electricity used by this sector (see Figure 3-12). In 2022, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,248.2 MMT CO_2 Eq., a 1.1 percent increase from 2021 emissions.

Through EPA's Greenhouse Gas Reporting Program (GHGRP), specific industrial sector trends can be discerned from the overall total EIA industrial fuel consumption data used for these calculations. For example, from 2021 to 2022, the underlying EIA data showed increased consumption of natural gas and petroleum and decreased consumption of coal in the industrial sector. The GHGRP data highlights that several industries contributed to these trends, including chemical manufacturing; pulp, paper and print; food processing, beverages and tobacco; minerals manufacturing; and agriculture-forest-fisheries.[18]

[17] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

[18] Further details on industrial sector combustion emissions are provided by EPA's GHGRP. See http://ghgdata.epa.gov/ghgp/main.do.

Figure 3-11: Industrial Production Indices (Index 2017=100)

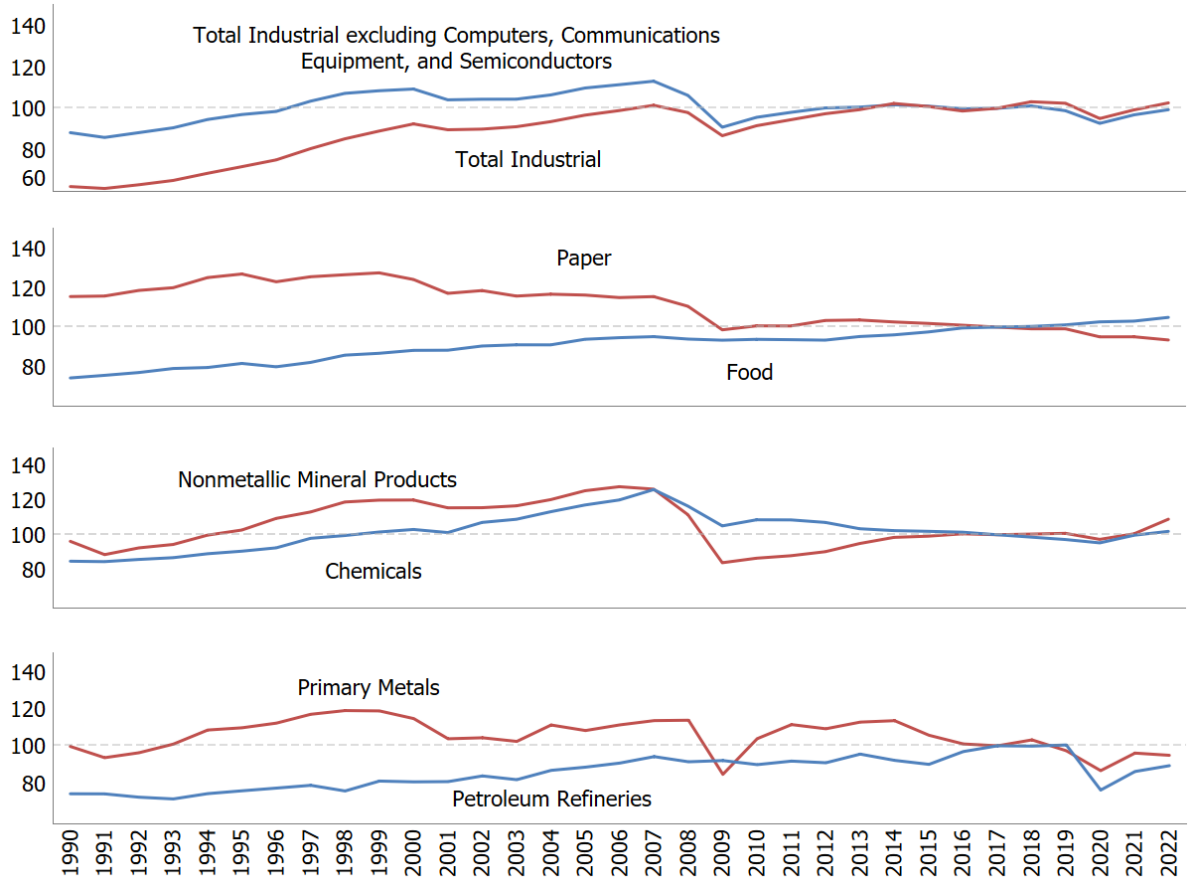
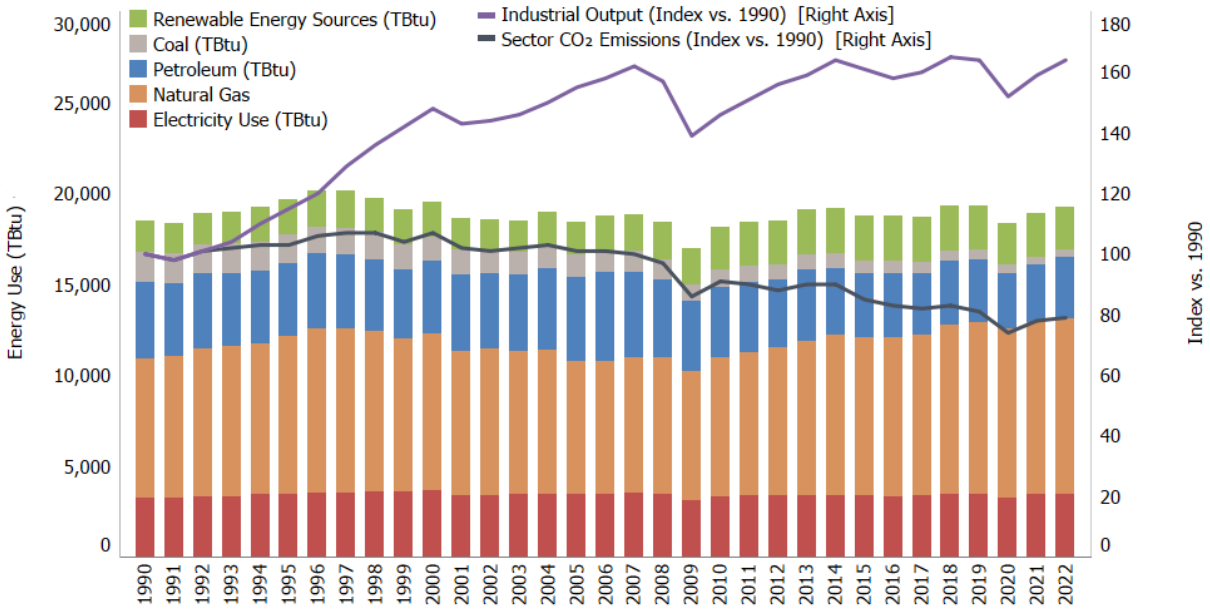


Figure 3-12: Fuels and Electricity Used in Industrial Sector, Industrial Output, and Total Sector CO_2 Emissions (Including Electricity)



Despite the growth in industrial output (65 percent) and the overall U.S. economy (114 percent) from 1990 to 2022, direct CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 8.6 percent over the same time series. A number of factors are assumed to result in decoupling of growth in industrial output from industrial greenhouse gas emissions, for example: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, and (2) energy-intensive industries such as steel are employing new methods, such as electric arc furnaces, that are less carbon-intensive than the older methods.

Box 3-3: Uses of Greenhouse Gas Reporting Program Data and Improvements in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's GHGRP has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For GHGRP 2010 through 2022 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the *Inventory's* use of EIA national fuel statistics to meet Paris Agreement and UNFCCC reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise.[19]

As with previous *Inventory* reports, the current effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the *Inventory* to the UNFCCC, progress was made on certain fuel types for specific industries and has been included in the Common Reporting Tables (CRTs) that are submitted to the UNFCCC along with this report.[20] The efforts in reconciling fuels focus on standard, common fuel types (e.g., natural gas, distillate fuel oil) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the CRTs should be viewed as an initial attempt at this exercise. Additional efforts will be made for future *Inventory* reports to improve the mapping of fuel types and examine ways to reconcile and coordinate any differences between facility-level data and national statistics. The current analysis includes the full time series presented in the CRTs. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2022 time period in the CRTs. It is believed that the current analysis has led to improvements in the presentation of data in the *Inventory*, but further work will be conducted, and future improvements will be realized in subsequent *Inventory* reports. This includes incorporating the latest MECS data as it becomes available.

Residential and Commercial Sectors

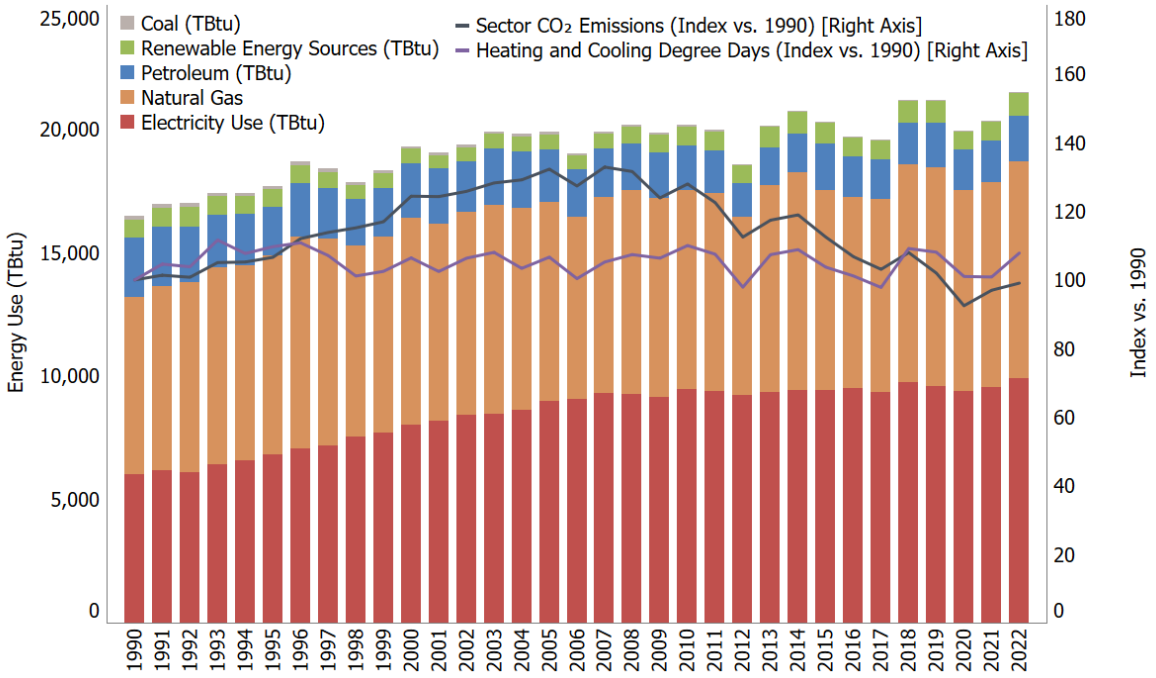
Emissions from the residential and commercial sectors have generally decreased since 2005. Short-term trends are often correlated with seasonal fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Population growth and a trend towards larger houses has led to increasing energy use over

[19] See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, at http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[20] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

the time series, while population migration to warmer areas and improved energy efficiency and building insulation have slowed the increase in energy use in recent years. Starting in around 2014, energy use and emissions begin to decouple due to decarbonization of the electric power sector (see Figure 3-13).

Figure 3-13: Fuels and Electricity Used in Residential and Commercial Sectors, Heating and Cooling Degree Days, and Total Sector CO_2 Emissions (Including Electricity)



In 2022, excluding indirect emissions from electricity use, the residential and commercial sectors accounted for 7 and 6 percent of CO_2 emissions from fossil fuel combustion, respectively; 39 and 13 percent of CH_4 emissions from fossil fuel combustion, respectively; and 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors are primarily attributable to building -related activities such as the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in the commercial sector and did not contribute to any energy use in the residential sector. Greenhouse gas emissions from commercial and residential buildings also increase substantially when emissions from electricity end-use are included, because the building sector uses 75 percent of the electricity generated in the United States (e.g., for heating, ventilation, and air conditioning; lighting; and appliances) (NREL 2023). In 2022, total emissions (CO_2, CH_4, and N_2O) from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 912.9 MMT CO_2 Eq. and 791.6 MMT CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from combined fossil fuel combustion and electricity use within the residential and commercial end-use sectors increased by 1.2 and 3.5 percent from 2021 to 2022, respectively. An increase in heating degree days (7.9 percent) and cooling degree days (4.3 percent) increased energy demand for heating and cooling in the residential and commercial sectors. This resulted in a 2.6 percent increase in residential sector electricity use. From 2021 to 2022 there was a 8.4 percent higher direct energy use in the commercial sector. In addition, a shift toward energy efficient products and more stringent energy efficiency standards for household equipment has contributed to a decrease in energy demand in households (EIA 2022), resulting in a decrease in energy-related emissions in the residential sector since 1990. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in total housing units and building attributes (e.g., larger sizes and improved insulation).

In 2022, combustion emissions from natural gas consumption represented 81 and 74 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. Carbon dioxide emissions from natural gas combustion in the residential and commercial sectors in 2022 increased by 5.2 percent and 6.6 percent from 2021, respectively.

U.S. Territories

Emissions from U.S. Territories are based on the fuel consumption in American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands. As described in the Methodology section of CO_2 from Fossil Fuel Combustion, this data is collected separately from the sectoral-level data available for the general calculations. As sectoral information is not available for U.S. Territories, CO_2, CH_4, and N_2O emissions are not presented for U.S. Territories in the tables above by sector, though the emissions will occur across all sectors and sources including stationary, transportation and mobile combustion sources.

Transportation Sector and Mobile Combustion

This discussion of transportation emissions follows the alternative method of presenting combustion emissions by allocating emissions associated with electricity generation to the transportation end-use sector, as presented in Table 1-9. Table 1-8 presents direct CO_2, CH_4, and N_2O emissions from all transportation sources (i.e., excluding emissions allocated to electricity consumption in the transportation end-use sector).

The transportation end-use sector and other mobile combustion accounted for 1,776.7 MMT CO_2 Eq. in 2022, which represented 37 percent of CO_2 emissions, 23 percent of CH_4 emissions, and 41 percent of N_2O emissions from fossil fuel combustion, respectively.[21] Fuel purchased in the U.S. for international aircraft and marine travel accounted for an additional 98.9 MMT CO_2 Eq. in 2022; these emissions are recorded as international bunkers and are not included in U.S. totals according to Paris Agreement and UNFCCC reporting protocols.

Transportation End-Use Sector

From 1990 to 2019, transportation emissions from fossil fuel combustion rose by 21 percent, followed by a reduction of 13 percent from 2019 to 2020, followed by an increase of 12 percent from 2020 to 2022. Overall, from 1990 to 2022, transportation emissions from fossil fuel combustion increased by 17 percent. The increase in transportation emissions from fossil fuel combustion from 1990 to 2022 was due, in large part, to increased demand for travel (see Figure 3-14). The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 47 percent from 1990 to 2022, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period. Between 2019 and 2020, emissions from light-duty vehicles fell by 11 percent, primarily the result of the COVID-19 pandemic and associated restrictions, such as people working from home and traveling less. Light-duty vehicle VMT rebounded in 2022 but is still estimated to be 2 percent below 2019 levels.

Commercial aircraft emissions decreased by 5 percent between 2019 and 2022 but have decreased 7 percent since 2007 (FAA 2024 and DOT 1991 through 2023).[22] Decreases in jet fuel emissions (excluding bunkers) started in 2007 due in part to improved operational efficiency that results in more direct flight routing, improvements in aircraft and engine technologies to reduce fuel burn and emissions, and the accelerated retirement of older, less fuel-efficient aircraft; however, the sharp decline in commercial aircraft emissions from 2019 to 2020 and their gradual recovery since is primarily due to COVID-19 impacts on scheduled passenger air travel.

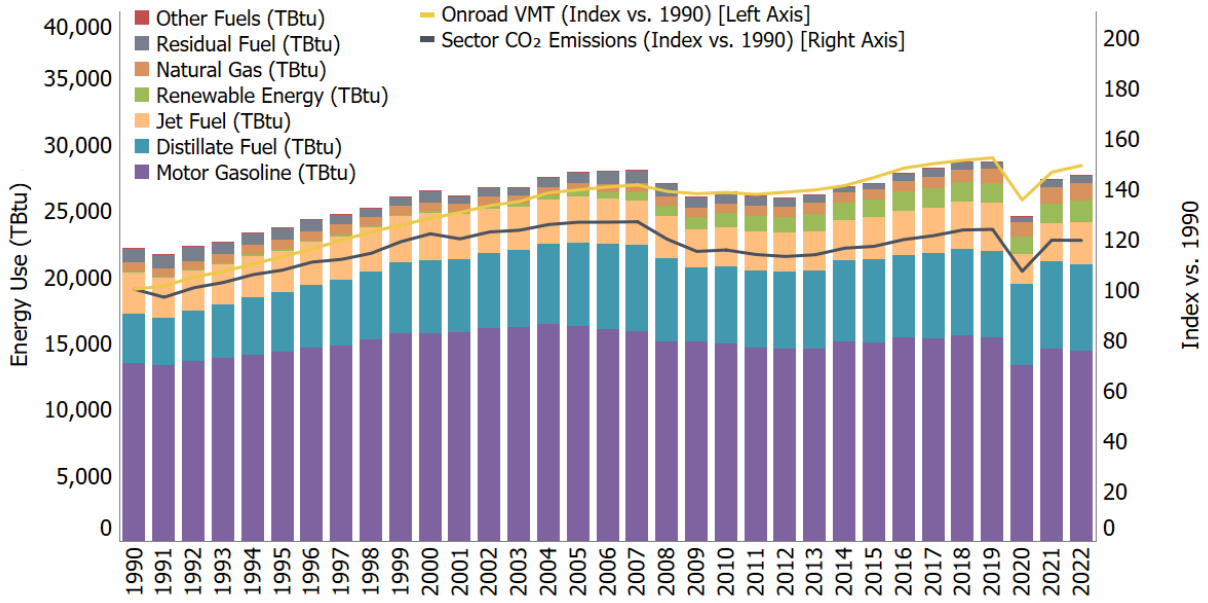
Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially

[21] Note that these totals include CO_2, CH_4 and N_2O emissions from some sources in the U.S. Territories (ships and boats, recreational boats, non-transportation mobile sources) and CH_4 and N_2O emissions from transportation rail electricity.

[22] Commercial aircraft consists of passenger aircraft, cargo, and other chartered flights.

diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 19 percent from 1990 to 2022. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

Figure 3-14: Fuels Used in Transportation Sector, On-road VMT, and Total Sector CO_2 Emissions



Notes: Distillate fuel, residual fuel, and jet fuel include adjustments for international bunker fuels. Distillate fuel and motor gasoline include adjustments for the sectoral allocation of these fuels. Other Fuels includes aviation gasoline and propane.

Source: Information on fuel consumption was obtained from EIA (2022).

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 19 percent (285.4 MMT CO_2 Eq.) between 1990 and 2022, an annualized increase of 0.6 percent. This includes a 24 percent increase in CO_2 emissions between 1990 and 2019, followed by a 13 percent decrease in 2020. Carbon dioxide emissions then increased by 11 percent between 2020 and 2022. Among domestic transportation sources, light-duty vehicles (including passenger cars and light-duty trucks) represented 57 percent of CO_2 emissions, medium- and heavy-duty trucks and buses 24 percent, commercial aircraft 7 percent, and other sources 11 percent. See Table 3-13 for a detailed breakdown of transportation CO_2 emissions by mode and fuel type.

Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Carbon dioxide emissions from the combustion of ethanol and biodiesel for transportation purposes, along with the emissions associated with the agricultural and industrial processes involved in the production of biofuel, are captured in other *Inventory* sectors.[23] Ethanol consumption from the transportation sector has increased from 0.7 billion gallons in 1990 to 12.9 billion gallons in 2022, while biodiesel

[23] Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA's Renewable Fuels Standards website. See https://www.epa.gov/renewable-fuel-standard-program.

consumption has increased from 0.01 billion gallons in 2001 to 1.6 billion gallons in 2022." For additional information, see Section 3.10 on biofuel consumption at the end of this chapter and Table A-74 in Annex 3.2.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,005.5 MMT CO_2 in 2022, an increase of 10 percent (91.2 MMT CO_2) from 1990. The increase in CO_2 emissions from passenger cars and light-duty trucks from 1990 to 2022 was due, in large part, to increased demand for travel as fleet-wide light-duty vehicle fuel economy was relatively stable (average new vehicle fuel economy declined slowly from 1990 through 2004 and then increased more rapidly from 2005 through 2022). Carbon dioxide emissions from passenger cars and light-duty trucks peaked at 1,145.5 MMT in 2004, and since then have declined about 12 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (see Figure 3-15) reflects the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty vehicle VMT grew only modestly for much of the period. Light-duty vehicle VMT grew by less than one percent or declined each year between 2005 and 2013, and again between 2017 and 2019. VMT grew at faster rates of 1.6 percent from 2014 to 2015, and 1.6 percent from 2015-2016. From 2019 to 2020, light-duty vehicle VMT declined by 11.0 percent due to COVID-19 pandemic; from 2020 to 2022 light-duty vehicle VMT rebounded as a part of the ongoing recovery from the pandemic, increasing by 9.8 percent.

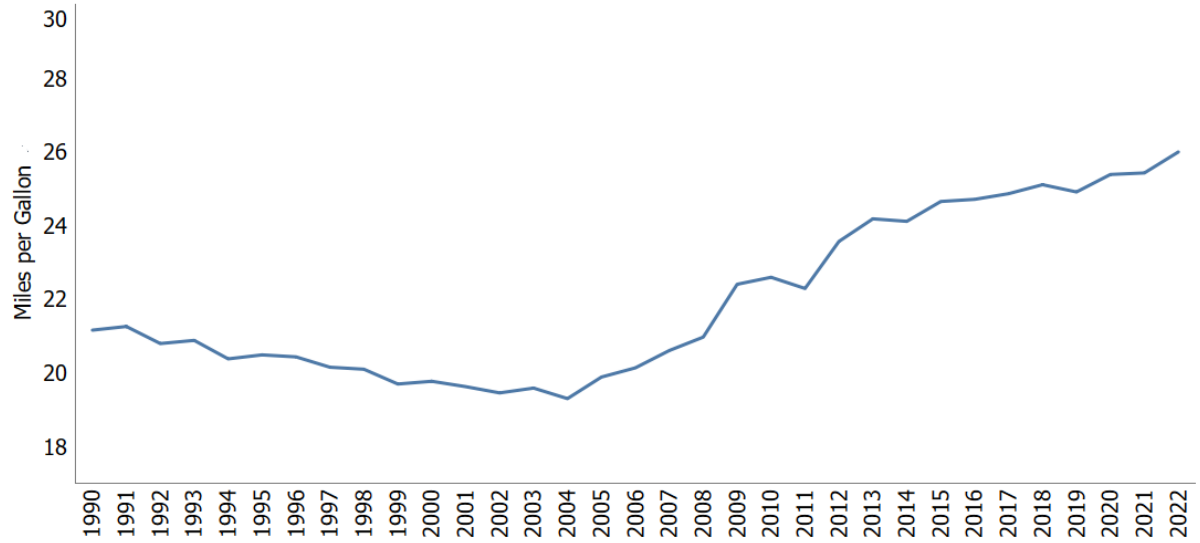
Average new vehicle fuel economy has improved almost every year since 2005 while the light-duty truck share of new vehicle sales decreased to about 33 percent of new vehicles in 2009 and has since varied from year to year between 36 and 63 percent. Since 2014, the light-duty truck share has steadily increased, reaching 62 percent of new vehicle sales in model year 2022. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

Medium- and heavy-duty truck CO_2 emissions increased by 73 percent from 1990 to 2022. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 72 percent between 1990 and 2022.

Carbon dioxide from the domestic operation of commercial aircraft increased by 18 percent (19.8 MMT CO_2) from 1990 to 2022. Across all categories of aviation, excluding international bunkers, CO_2 emissions decreased by 11 percent (20.8 MMT CO_2) between 1990 and 2022.[24] Carbon dioxide emissions from military aircraft decreased 65 percent between 1990 and 2022. Commercial aircraft CO_2 emissions increased 27 percent between 1990 and 2007, dropped 2 percent from 2007 to 2019, dropped another 33 percent from 2019 to 2020, then increased by 30 percent from 2020 to 2022. Overall, this represents a change of approximately 18 percent between 1990 and 2022. Transportation sources also produce CH_4 and N_2O; these emissions are included in Figure 3-14 and Table 3-15 and in the CH_4 and N_2O from Mobile Combustion section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

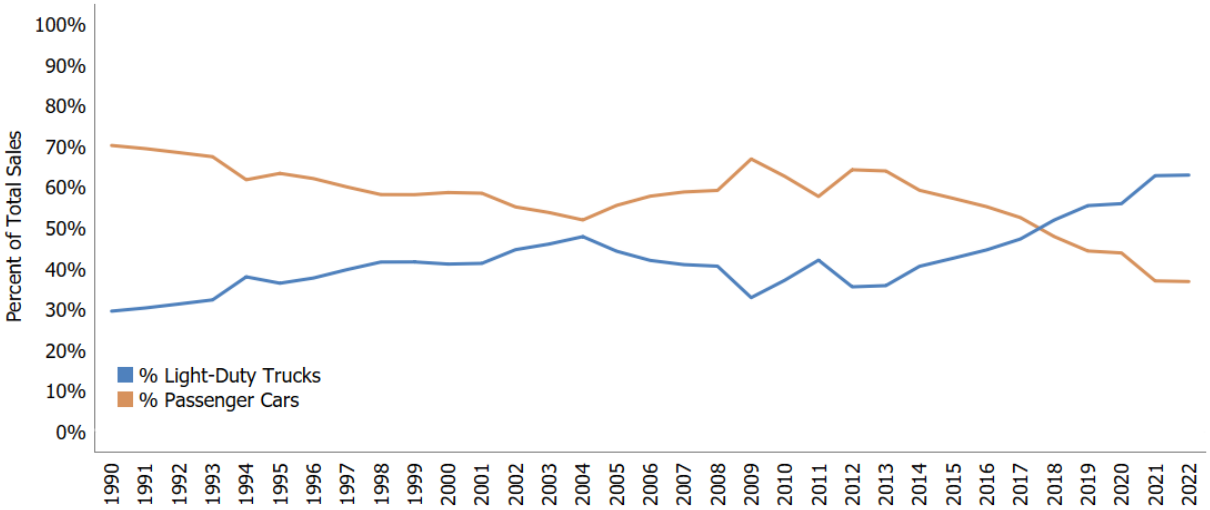
[24] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-15: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2022



Source: EPA (2023).

Figure 3-16: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2022



Source: EPA (2023).

Table 3-13: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO_2 Eq.)

Fuel/Vehicle Type	1990	2005	2018	2019	2020	2021	2022
Gasoline[a]	**958.9**	**1,150.1**	**1,097.0**	**1,086.5**	**936.9**	**1,028.7**	**1,014.5**
Passenger Cars	612.8	518.9	382.5	380.0	328.0	360.5	356.0
Light-Duty Trucks	283.6	583.4	667.6	658.6	565.7	619.9	609.5
Medium- and Heavy-Duty Trucks[b]	42.8	28.1	26.2	27.0	24.1	27.4	27.9
Buses	2.1	1.1	2.7	2.8	2.5	2.9	2.9
Motorcycles	3.4	4.9	7.3	7.4	6.6	7.4	7.4
Recreational Boats[c]	14.3	13.7	10.7	10.7	9.9	10.6	10.8

Distillate Fuel Oil (Diesel)[a]	**274.6**	**472.1**	**486.6**	**484.1**	**455.2**	**488.1**	**483.9**
Passenger Cars	9.4	2.2	2.8	2.7	2.5	2.7	2.7
Light-Duty Trucks	8.4	30.4	31.2	31.2	30.2	33.3	33.8
Medium- and Heavy-Duty Trucks[b]	189.0	357.2	371.5	373.0	353.5	380.1	375.6
Buses	11.1	15.5	20.4	20.7	19.8	21.4	21.4
Rail	35.5	46.1	38.5	36.0	31.2	32.5	32.5
Recreational Boats[c]	2.7	2.9	2.8	2.9	2.6	2.8	3.0
Ships and Non-Recreational Boats[d]	6.8	8.4	9.3	7.5	7.6	7.8	7.8
International Bunker Fuels[e]	*11.7*	*9.5*	*10.0*	*10.1*	*7.8*	*7.4*	*7.2*
Jet Fuel	**222.3**	**249.5**	**255.2**	**258.5**	**160.4**	**203.5**	**231.5**
Commercial Aircraft[f]	109.9	132.7	129.6	136.7	91.3	119	129.7
Military Aircraft	35.7	19.8	12.1	12.2	11.7	12.5	12.4
General Aviation Aircraft	38.5	36.8	30.6	31.4	17.6	21.1	22.7
International Bunker Fuels[e]	*38.2*	*60.2*	*83.0*	*78.3*	*39.8*	*50.8*	*66.6*
International Bunker Fuels from Commercial Aviation	*30.0*	*55.6*	*79.8*	*75.1*	*36.7*	*47.6*	*63.5*
Aviation Gasoline	**3.1**	**2.4**	**1.5**	**1.6**	**1.4**	**1.5**	**1.5**
General Aviation Aircraft	3.1	2.4	1.5	1.6	1.4	1.5	1.5
Residual Fuel Oil	**76.3**	**62.9**	**45.4**	**39.7**	**29.4**	**46.2**	**47.3**
Ships and Non-Recreational Boats[e]	22.6	19.3	14.0	14.5	7.3	24.2	22.9
International Bunker Fuels[e]	*53.7*	*43.6*	*31.4*	*25.2*	*22.1*	*21.9*	*24.4*
Natural Gas[i]	**36.0**	**33.1**	**50.9**	**58.9**	**58.7**	**65.2**	**70.2**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Buses	+	0.2	0.5	0.5	0.6	0.6	0.7
Pipeline[g]	36.0	32.8	50.3	58.3	58.0	64.4	69.3
LPG[i]	**1.4**	**1.8**	**0.8**	**0.8**	**0.5**	**0.6**	**0.6**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	0.1	0.1	+	+	+	+	+
Medium- and Heavy-Duty Trucks[b]	1.3	0.9	0.1	0.1	0.1	+	+
Buses	+	0.7	0.7	0.7	0.5	0.6	0.6
Electricity[k]	**3.0**	**4.7**	**4.8**	**4.8**	**4.1**	**5.0**	**6.1**
Passenger Cars	+	+	1.2	1.4	1.3	1.8	2.4
Light-Duty Trucks	+	+	0.2	0.2	0.3	0.7	1.1
Buses	+	+	+	+	0.1	0.1	0.1
Rail	3.0	4.7	3.4	3.1	2.4	2.5	2.5
Total [e,j]	**1,472.0**	**1,863.3**	**1,817.9**	**1,821.4**	**1,576.9**	**1758.6**	**1,757.4**
International Bunker Fuels	*103.6*	*113.3*	*124.3*	*113.6*	*69.6*	*80.2*	*98.2*
Biofuels-Ethanol[h]	*4.1*	*21.6*	*78.6*	*78.7*	*68.1*	*75.4*	*75.0*
Biofuels-Biodiesel[h]	*0.0*	*0.9*	*17.9*	*17.1*	*17.7*	*16.1*	*15.6*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] On-road fuel consumption data from FHWA Table MF-21 and MF-27 were used to determine total on-road use of motor gasoline and diesel fuel (FHWA 1996 through 2023). Ratios developed from MOVES3 output are used to apportion FHWA fuel consumption data to vehicle type and fuel type (see Annex 3.2 for information about the MOVES model).

[b] Includes medium- and heavy-duty trucks over 8,500 lbs.

[c] In 2014, EPA incorporated the NONROAD2008 model into the MOVES model framework. The current *Inventory* uses the Nonroad component of MOVES3 for years 1999 through 2022. See Annex 3.2 for information about the MOVES model.

[d] Note that large year over year fluctuations in emission estimates partially reflect nature of data collection for these sources.

[e] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates of international bunker fuel-related emissions are presented for informational purposes.

[f] Commercial aircraft, as modeled in FAA's Aviation Environmental Design Tool (AEDT), consists of passenger aircraft, cargo, and other chartered flights.

[g] Pipelines reflect CO_2 emissions from natural gas-powered pipelines transporting natural gas.

[h] Ethanol and biodiesel estimates are presented for informational purposes only. See Section 3.10 of this chapter and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and Paris Agreement and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

[i] Transportation sector natural gas and LPG consumption are based on data from EIA (2023b). Prior to the 1990 to 2015 *Inventory*, data from DOE TEDB were used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 to 2016 *Inventory* and apply to the 1990 to 2022 time period.

[j] Includes emissions from rail electricity.

[k] Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales and engine efficiency data, as outlined in Browning (2018). In prior *Inventory* years, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes apply to the 2010 through 2022 time period.

Notes: This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction/mining equipment; it also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation. In addition, this table does not include CO_2 emissions from U.S. Territories, since these are covered in a separate chapter of the *Inventory*. Totals may not sum due to independent rounding.

Mobile Fossil Fuel Combustion CH_4 and N_2O Emissions

Mobile combustion includes emissions of CH_4 and N_2O from all transportation sources identified in the U.S. *Inventory* with the exception of pipelines and electric locomotives;[25] mobile sources also include non-transportation sources such as construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources (e.g., snowmobiles, lawnmowers, etc.).[26] Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-14 and Table 3-15 provide mobile fossil fuel CH_4 and N_2O emission estimates in MMT CO_2 Eq.[27]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.4 percent) and was the fifth largest source of national N_2O emissions (4.3 percent) in 2022. From 1990 to 2022, mobile source CH_4 emissions declined by 64 percent, to 2.6 MMT CO_2 Eq. (93 kt), due largely to emissions control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 57 percent, to 16.7 MMT CO_2 Eq. (63 kt) in 2022. Earlier generation control technologies initially resulted in elevated N_2O emissions, causing a 31 percent increase in N_2O emissions from mobile sources between 1990 and 1997. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in a 67 percent decrease in mobile source N_2O emissions from 1997 to 2022 (see Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars, light-duty trucks, and non-highway sources. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles.

[25] Emissions of CH_4 from natural gas systems are reported separately. More information on the methodology used to calculate these emissions are included in this chapter and Annex 3.4.

[26] See the methodology sub-sections of the CO_2 from Fossil Fuel Combustion and CH_4 and N_2O from Mobile Combustion sections of this chapter. Note that N_2O and CH_4 emissions are reported using different categories than CO_2. CO_2 emissions are reported by end-use sector (transportation, industrial, commercial, residential, U.S. Territories), and generally adhere to a top-down approach to estimating emissions. CO_2 emissions from non-transportation mobile sources (e.g., lawn and garden equipment, farm equipment, construction equipment) are allocated to their respective end-use sector (i.e., construction equipment CO_2 emissions are included in the Industrial end-use sector instead of the transportation end-use sector). CH_4 and N_2O emissions are reported using the "mobile combustion" category, which includes non-transportation mobile sources. CH_4 and N_2O emission estimates are bottom-up estimates, based on total activity (fuel use, VMT) and emissions factors by source and technology type. These reporting schemes are in accordance with IPCC guidance. For informational purposes only, CO_2 emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 3.2.

[27] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2022.

Figure 3-17: Mobile Source CH_4 and N_2O Emissions

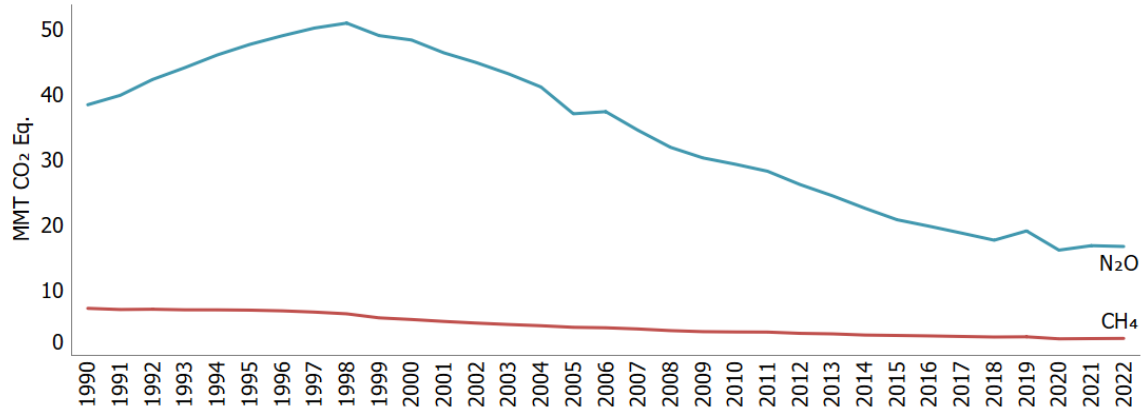


Table 3-14: CH_4 Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2018	2019	2020	2021	2022
Gasoline On-Road[b]	**5.8**	**2.4**	**0.9**	**1.0**	**0.8**	**0.8**	**0.7**
Passenger Cars	3.8	1.2	0.3	0.3	0.2	0.2	0.2
Light-Duty Trucks	1.5	1.0	0.5	0.6	0.5	0.5	0.5
Medium- and Heavy-Duty Trucks and Buses	0.5	0.1	+	+	+	+	+
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**+**	**0.1**	**+**	**+**	**+**	**+**
Non-Road[c]	**1.4**	**1.8**	**1.7**	**1.7**	**1.6**	**1.6**	**1.7**
Ships and Boats	0.4	0.5	0.5	0.4	0.4	0.5	0.5
Rail[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[e]	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[f]	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Other[g]	0.5	0.7	0.8	0.8	0.8	0.7	0.8
Total	**7.2**	**4.3**	**2.8**	**2.9**	**2.5**	**2.6**	**2.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1. VMT estimates from FHWA are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model).

[c] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA 2023b).

[d] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 to 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[f] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[g] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table 3-15: N_2O Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2018	2019	2020	2021	2022
Gasoline On-Road[b]	**32.0**	**28.5**	**7.0**	**8.1**	**6.3**	**6.0**	**5.3**
Passenger Cars	22.4	13.3	2.5	2.5	2.0	1.9	1.6
Light-Duty Trucks	8.7	14.0	4.3	5.4	4.2	3.9	3.5
Medium- and Heavy-Duty Trucks and Buses	0.8	1.2	0.2	0.2	0.1	0.1	0.1
Motorcycles	+	+	0.1	0.1	0.1	0.1	0.1
Diesel On-Road[b]	**0.2**	**0.4**	**3.0**	**3.2**	**3.0**	**3.3**	**3.5**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	0.3	0.2	0.2	0.3	0.3
Medium- and Heavy-Duty Trucks	0.2	0.3	2.4	2.7	2.5	2.7	2.9
Medium- and Heavy-Duty Buses	+	+	0.3	0.3	0.2	0.3	0.3
Alternative Fuel On-Road	**+**	**+**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Road[c]	**6.2**	**8.1**	**7.5**	**7.6**	**6.7**	**7.4**	**7.8**
Ships and Boats	0.2	0.2	0.2	0.2	0.1	0.3	0.3
Rail[d]	0.2	0.3	0.3	0.2	0.2	0.2	0.2
Aircraft	1.5	1.6	1.4	1.5	1.0	1.3	1.4
Agricultural Equipment[e]	1.2	1.4	1.1	1.1	1.1	1.1	1.1
Construction/Mining Equipment[f]	1.2	1.9	1.6	1.7	1.6	1.7	1.7
Other[g]	1.8	2.8	2.9	2.9	2.7	2.9	3.2
Total	**38.4**	**37.0**	**17.7**	**19.1**	**16.1**	**16.8**	**16.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1. VMT estimates from FHWA are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model).

[c] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA 2023a).

[d] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 through 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[f] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[g] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: Totals may not sum due to independent rounding.

CO_2 from Fossil Fuel Combustion

Methodology and Time-Series Consistency

CO_2 emissions from fossil fuel combustion are estimated in line with a Tier 2 method described by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Chapter 2, Figure 2.1 decision tree and

available data on energy use and country specific fuel carbon contents with some exceptions as discussed below.[28] A detailed description of the U.S. methodology is presented in Annex 2.1, and is characterized by the following steps:

1. *Determine total fuel consumption by fuel type and sector*. Total fossil fuel consumption for each year is estimated by aggregating consumption data by end-use sector (e.g., commercial, industrial), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil). Fuel consumption data for the United States were obtained directly from the EIA of the U.S. Department of Energy (DOE), primarily from the *Monthly Energy Review* (EIA 2024a). EIA data include fuel consumption statistics from the 50 U.S. states and the District of Columbia, including tribal lands. The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from EIA's International Energy Statistics (EIA 2024b).[29]

   For consistency of reporting, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA on an annual basis and used in this *Inventory* are predominantly from mid-stream or conversion energy consumers such as refiners and electric power generators. These annual surveys are supplemented with end-use energy consumption surveys, such as the Manufacturing Energy Consumption Survey, that are conducted on a periodic basis (every four years). These consumption datasets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[30]

   Also, note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). Fuel consumption activity data presented here have not been adjusted to correspond to international standards, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[31]

2. *Subtract uses accounted for in the Industrial Processes and Product Use chapter*. Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—were reallocated to the Industrial Processes and Product Use chapter, as they were consumed during non-energy-related industrial activity. To make these adjustments, additional data were collected from AISI (2004 through 2021), Coffeyville (2012), U.S. Census Bureau (2001 through 2011), EIA (2024a, 2023c, 2023d), USAA (2008 through 2021), USGS (1991 through 2020), (USGS 2019), USGS (2014 through 2021a), USGS (2014 through 2021b), USGS (1995 through 2013), USGS (1995, 1998, 2000, 2001, 2002, 2007), USGS (2021a), USGS (1991 through 2015a), USGS (1991 through 2020), USGS (2014 through 2021a), USGS (1991 through 2015b), USGS (2021b), USGS (1991 through 2020).[32]

3. *Adjust for biofuels and petroleum denaturant*. Fossil fuel consumption estimates are adjusted downward to exclude fuels with biogenic origins and avoid double counting in petroleum data statistics. Carbon

[28] The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

[29] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed total emissions of 22.6 MMT CO_2 Eq. in 2022.

[30] See IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

[31] A crude convention to convert between gross and net calorific values is to multiply the heat content of solid and liquid fossil fuels by 0.95 and gaseous fuels by 0.9 to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics, however, are generally presented using net calorific values.

[32] See sections on Iron and Steel Production and Metallurgical Coke Production, Ammonia Production and Urea Consumption, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, Aluminum Production, and Silicon Carbide Production and Consumption in the Industrial Processes and Product Use chapter.

dioxide emissions from ethanol added to motor gasoline and biodiesel added to diesel fuel are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF, therefore, fuel consumption estimates are adjusted to remove ethanol and biodiesel.[33] For the years 1993 through 2008, petroleum denaturant is currently included in EIA statistics for both natural gasoline and finished motor gasoline. To avoid double counting, petroleum denaturant is subtracted from finished motor gasoline for these years.[34]

4. *Adjust for exports of CO_2.* Since October 2000, the Dakota Gasification Plant has been exporting CO_2 produced in the coal gasification process to Canada by pipeline. Because this CO_2 is not emitted to the atmosphere in the United States, the associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 is subtracted from EIA (2023d) coal consumption statistics that are used to calculate greenhouse gas emissions from the Energy Sector. The associated fossil fuel is the total fossil fuel burned at the plant with the CO_2 capture system multiplied by the fraction of the plant's total site-generated CO_2 that is recovered by the capture system. To make these adjustments, data for CO_2 exports were collected from Environment and Climate Change Canada (2022). A discussion of the methodology used to estimate the amount of CO_2 captured and exported by pipeline is presented in Annex 2.1.

5. *Adjust sectoral allocation of distillate fuel oil and motor gasoline.* EPA conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration that indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel and motor gasoline consumption were adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2008 through 2022), Benson (2002 through 2004), DOE (1993 through 2020), EIA (2007), EIA (2024a), EPA (2022), and FHWA (1996 through 2023).[35]

6. *Adjust for fuels consumed for non-energy uses*. U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. These are fossil fuels that are manufactured into plastics, asphalt, lubricants, or other products. Depending on the end-use, this can result in storage of some or all of the carbon contained in the fuel for a period of time. As the emission pathways of carbon used for non-energy purposes are vastly different than fuel combustion (since the carbon in these fuels ends up in products instead of being combusted), these emissions are estimated separately in Section3.2. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption were provided by EIA (2023c).

7. *Subtract consumption of international bunker fuels.* According to the Paris Agreement and UNFCCC reporting guidelines emissions from international transport activities, or bunker fuels, should not be included in national totals. U.S. energy consumption statistics include these bunker fuels (e.g., distillate fuel oil, residual fuel oil, and jet fuel) as part of consumption by the transportation end-use sector, however, so emissions from international transport activities were calculated separately following the same procedures used to calculate emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of carbon content).[36] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Logistics Agency Energy (DLA Energy) of the U.S. Department of Defense (DoD) (DLA Energy 2022) supplied data on military jet fuel and marine fuel use.

---

[33] Natural gas energy statistics from EIA (2023a) are already adjusted downward to account for biogas in natural gas.

[34] These adjustments are explained in greater detail in Annex 2.1.

[35] Bottom-up gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2021).

[36] See International Bunker Fuels section in this chapter for a more detailed discussion.

Commercial jet fuel use was estimated based on data from FAA (2024) and DOT (1991 through 2022); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2022) for 1990 through 2001 and 2007 through 2020, and DHS (2008) for 2003 through 2006.[37] Consumption of these fuels was subtracted from the corresponding fuels totals in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail in Section 3.9.

8. *Determine the total carbon content of fuels consumed.* Total carbon was estimated by multiplying the amount of fuel consumed by the amount of carbon in each fuel. This total carbon estimate defines the maximum amount of carbon that could potentially be released to the atmosphere if all of the carbon in each fuel was converted to CO_2. A discussion of the methodology and sources used to develop the carbon content coefficients are presented in Annexes 2.1 and 2.2.

9. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 7), the carbon content of the fuels consumed, and the fraction of carbon that is oxidized. The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Annex 2.1). Carbon emissions were multiplied by the molecular-to-atomic weight ratio of CO_2 to carbon (44/12) to obtain total CO_2 emitted from fossil fuel combustion in million metric tons (MMT).

10. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it is such a large consumer of fossil fuels in the United States. For fuel types other than jet fuel, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Heat contents and densities were obtained from EIA (2023c) and USAF (1998).[38]

    - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2023); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from EPA's MOVES model and DOE (1993 through 2022).[39,40]

    - For non-road vehicles, activity data were obtained from AAR (2008 through 2022), APTA (2007 through 2022), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), BTS (2019 through 2022), DLA Energy (2022), DOC (1991 through 2022), DOE (1993 through 2022), DOT (1991 through 2022), EIA (2009a), EIA (2023a), EIA (2002), EIA (1991 through 2022), EPA (2022),[41] and Gaffney (2007).

[37] Data for 2002 were interpolated due to inconsistencies in reported fuel consumption data.

[38] For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.8, respectively.

[39] On-road fuel consumption data from FHWA Table MF-21 and MF-27 were used to determine total on-road use of motor gasoline and diesel fuel (FHWA 1996 through 2020). Data for 2021 is proxied using FHWA Traffic Volume Travel Trends. Ratios developed from MOVES3 output are used to apportion FHWA fuel consumption data to vehicle type and fuel type (see Annex 3.2 for information about the MOVES model).

[40] Transportation sector natural gas and LPG consumption are based on data from EIA (2024a). In previous Inventory years, data from DOE (1993 through 2022) TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium- and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 through 2015 Inventory and apply to the time period from 1990 to 2015.

[41] In 2014, EPA incorporated the NONROAD2008 model into the MOVES model framework (EPA 2022b). The current *Inventory* uses the Nonroad component of MOVES3 for years 1999 through 2022.

- For jet fuel used by aircraft, CO_2 emissions from commercial aircraft were developed by the U.S. Federal Aviation Administration (FAA) using a Tier 3B methodology, consistent IPCC (2006) (see Annex 3.3). Carbon dioxide emissions from other aircraft were calculated directly based on reported consumption of fuel as reported by EIA. Allocation to domestic military uses was made using DoD data (see Annex 3.8). General aviation jet fuel consumption is calculated as the remainder of total jet fuel use (as determined by EIA) nets all other jet fuel use as determined by FAA and DoD. For more information, see Annex 3.2.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. Due to data availability and sources, some adjustments outlined in the methodology above are not applied consistently across the full 1990 to 2022 time series. As described in greater detail in Annex 2.1, to align with EIA's methodology for calculating motor gasoline consumption, petroleum denaturant adjustments are applied to motor gasoline consumption only for the period 1993 through 2008. In addition to ensuring time-series consistency, to ensure consistency in reporting between the *Inventory* and the Canadian National Greenhouse Gas Inventory, the amount of associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 from the Dakota Gasification Plant is adjusted to align with the Canadian National Greenhouse Gas Inventory (Environment and Climate Change Canada 2022). This adjustment is explained in greater detail in Annex 2.1. As discussed in Annex 5, data are unavailable to include estimates of CO_2 emissions from any liquid fuel used in pipeline transport or non-hazardous industrial waste incineration, but those emissions are assumed to be insignificant.

Box 3-4: Carbon Intensity of U.S. Energy Consumption

The amount of carbon emitted from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that carbon that is oxidized. Fossil fuels vary in their average carbon content, ranging from about 53 MMT CO_2 Eq./QBtu for natural gas to upwards of 95 MMT CO_2 Eq./QBtu for coal and petroleum coke (see Tables A-42 and A-43 in Annex 2.1 for carbon contents of all fuels). In general, the carbon content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 3-16 provides a time series of the carbon intensity of direct emissions for each sector of the U.S. economy. The time series incorporates only the energy from the direct combustion of fossil fuels in each sector. For example, the carbon intensity for the residential sector does not include the energy from or emissions related to the use of electricity for lighting, as it is instead allocated to the electric power sector. For the purposes of maintaining the focus of this section, renewable energy and nuclear energy are not included in the energy totals used in Table 3-16 in order to focus attention on fossil fuel combustion as detailed in this chapter. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest carbon intensity, which is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector has predominantly declined since 1990 as commercial businesses shift away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher carbon intensities over this period. The carbon intensity of the transportation sector was closely related to the carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO_2 Eq./QBtu), which were the primary sources of energy. Lastly, the electric power sector had the highest carbon intensity due to its heavy reliance on coal for generating electricity.

Table 3-16: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO_2 Eq./QBtu)

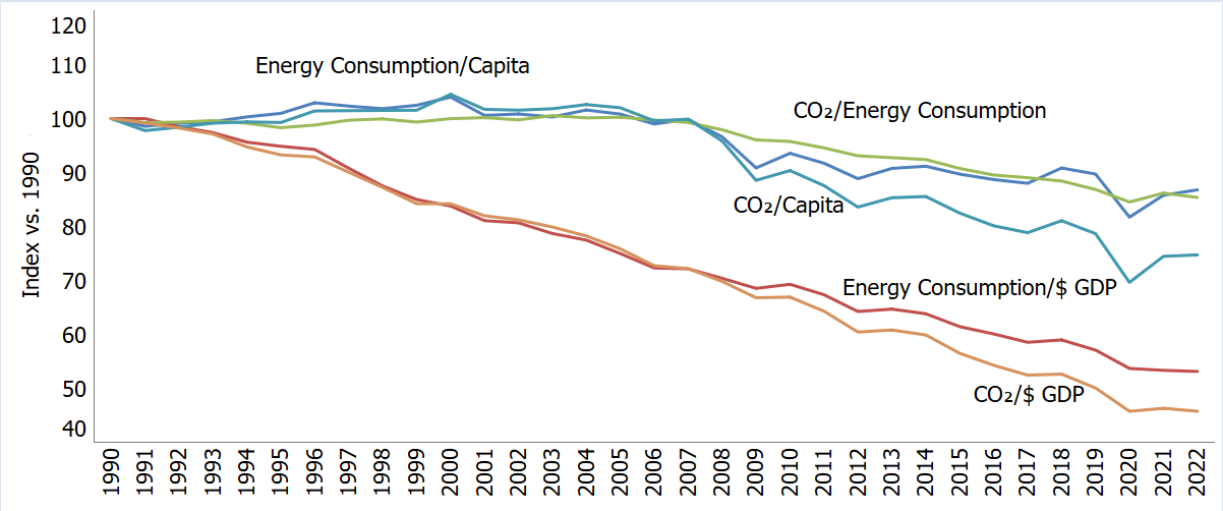
Sector	1990	2005	2018	2019	2020	2021	2022
Residential[a]	57.4	56.8	55.3	55.3	55.1	55.2	55.2
Commercial[a]	59.7	57.8	56.0	56.2	56.3	56.2	56.5
Industrial[a]	64.8	64.6	60.5	60.2	59.6	59.6	59.6
Transportation[a]	71.1	71.5	71.0	70.9	70.8	70.9	70.8
Electric Power[b]	87.3	85.8	75.5	72.9	70.5	72.4	70.9

U.S. Territories[c]	73.1	73.4	70.4	70.8	71.7	70.1	71.3
All Sectors[c]	**73.1**	**73.6**	**68.3**	**67.3**	**66.6**	**67.0**	**66.5**

[a] Does not include electricity or renewable energy consumption.
[b] Does not include electricity produced using nuclear or renewable energy.
[c] Does not include nuclear or renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption. Totals may not sum due to independent rounding.

For the time period of 1990 through about 2008, the carbon intensity of U.S. energy consumption was fairly constant, as the proportion of fossil fuels used by the individual sectors did not change significantly over that time. Starting in 2008 the carbon intensity of U.S. energy consumption has decreased, reflecting the shift from coal to natural gas in the electric power sector during that time period. Per capita energy consumption fluctuated little from 1990 to 2007, but then started decreasing after 2007 and, in 2022, was approximately 13.2 percent below levels in 1990 (see Figure 3-18). To differentiate these estimates from those of Table 3-16, the carbon intensity trend shown in Figure 3-18 and described below includes nuclear and renewable energy EIA data to provide a comprehensive economy-wide picture of energy consumption. Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2024).

Figure 3-18: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2023c), EPA (2010), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the

amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990). See also Annex 2.2 for a discussion of uncertainties associated with fuel carbon contents. Recent updates to carbon factors for natural gas and coal utilized the same approach as previous Inventories with updated recent data, therefore, the uncertainty estimates around carbon contents of the different fuels as outlined in Annex 2.2 were not impacted and the historic uncertainty ranges still apply.

Although national statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs), but a commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to some minor challenges in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

To calculate the total CO_2 emission estimate from energy-related fossil fuel combustion, the amount of fuel used in non-energy production processes were subtracted from the total fossil fuel consumption. The amount of CO_2 emissions resulting from non-energy related fossil fuel use has been calculated separately and reported in the Carbon Emitted from Non-Energy Uses of Fossil Fuels section of this report (Section 3.2). These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with carbon emitted from non-energy uses of fossil fuels can be found within that section of this chapter.

Various sources of uncertainty surround the estimation of emissions from international bunker fuels, which are subtracted from the U.S. totals (see the detailed discussions on these uncertainties provided in Section 3.9). Another source of uncertainty is fuel consumption by U.S. Territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty states and the District of Columbia. Therefore, estimating both emissions and bunker fuel consumption by these territories is difficult.

Uncertainties in the emission estimates presented above also result from the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom-up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions.

The uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, with @RISK software. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models. About 170 input variables were modeled for CO_2 from energy-related fossil fuel combustion (including about 20 for non-energy fuel consumption and about 20 for International Bunker Fuels).

In developing the uncertainty estimation model, uniform distributions were assumed for all activity-related input variables and emission factors, based on the SAIC/EIA (2001) report.[42] Triangular distributions were assigned for the oxidization factors (or combustion efficiencies). The uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001) and on conversations with various agency personnel.[43]

---

[42] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[43] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

The uncertainty ranges for the activity-related input variables were typically asymmetric around their inventory estimates; the uncertainty ranges for the emissions factors were symmetric. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainties associated with these variables (SAIC/EIA 2001).[44] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo sampling.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-17. Fossil fuel combustion CO_2 emissions in 2022 were estimated to be between 4,603.1 and 4,905.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 4 percent above the 2022 emission estimate of 4,699.4 MMT CO_2 Eq.

Table 3-17: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-Related Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq. and Percent)

Fuel/Sector	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal[b]	**898.8**	**868.6**	**983.9**	**-3%**	**9%**
Residential	NO	NO	NO	NO	NO
Commercial	1.4	1.3	1.6	-5%	15%
Industrial	43.0	41.0	49.9	-5%	16%
Transportation	NO	NO	NO	NO	NO
Electric Power	851.5	818.9	933.8	-4%	10%
U.S. Territories	2.9	2.5	3.4	-12%	19%
Natural Gas[b]	**1,706.8**	**1,687.3**	**1,784.4**	**-1%**	**5%**
Residential	272.0	264.4	291.1	-3%	7%
Commercial	192.3	186.9	205.8	-3%	7%
Industrial	510.4	494.9	548.0	-3%	7%
Transportation	70.2	68.2	75.1	-3%	7%
Electric Power	659.3	640.1	693.0	-3%	5%
U.S. Territories	2.7	2.4	3.2	-12%	17%
Petroleum[b]	**2,093.4**	**1,966.4**	**2,215.9**	**-6%**	**6%**
Residential	62.1	58.6	65.4	-6%	5%
Commercial	65.1	61.5	68.5	-5%	5%
Industrial	247.6	193.3	302.0	-22%	22%
Transportation	1,681.1	1,573.2	1,785.6	-6%	6%
Electric Power	20.5	19.7	22.0	-4%	7%
U.S. Territories	17.0	15.7	18.7	-7%	10%
Geothermal	**0.4**	**0.2**	**1.0**	**-48%**	**173%**
Electric Power	0.4	0.2	1.0	-48%	173%
Total (including Geothermal)[b]	**4,699.4**	**4,603.1**	**4,905.2**	**-2%**	**4%**

NO (Not Occurring)

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

Note: Totals may not sum due to independent rounding.

[44] Although, in general, random uncertainties are the main focus of statistical uncertainty analysis, when the uncertainty estimates are elicited from experts, their estimates include both random and systematic uncertainties. Hence, both these types of uncertainties are represented in this uncertainty analysis.

QA/QC and Verification

In order to ensure the quality of the CO_2 emission estimates from fossil fuel combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

One area of QA/QC and verification is to compare the estimates and emission factors used in the *Inventory* with other sources of CO_2 emissions reporting. Two main areas and sources of data were considered. The first is a comparison with the EPA GHGRP combustion data (Subpart C) for stationary combustion sources excluding the electric power sector. This mainly focused on considering carbon factors for natural gas. The second comparison is with the EPA Air Markets Program data for electric power production. This considered carbon factors for coal and natural gas used in electric power production.

The EPA GHGRP collects greenhouse gas emissions data from large emitters including information on fuel combustion. This excludes emissions from mobile sources and smaller residential and commercial sources, those emissions are covered under supplier reporting (Subparts MM and NN) and are areas for further research. Fuel combustion CO_2 data reported in 2022 was 2,082.6 MMT CO_2. Of that, 1,577.7 MMT CO_2 was from electricity production. Therefore, the non-electric power production fuel combustion reporting was a fraction of the total covered by the *Inventory* under fossil fuel combustion. Furthermore, reporters under the GHGRP can use multiple methods of calculating emissions; one method is to use the default emission factors provided in the rule, while another is based on a tier 3 approach using their own defined emission factors. Based on data from reporters on approach used, it was determined that only about 10 percent of natural gas combustion emissions were based on a tier 3 approach. Given the small sample size compared to the overall *Inventory* calculations for natural gas combustion EPA determined it was not reasonable to consider the GHGRP tier 3 natural gas factors at this time. A more detailed analysis was done on upstream oil and gas natural gas combustion emissions using the GHGRP data as discussed in Annex 2.2.

EPA collects detailed sulfur dioxide (SO_2), nitrogen oxides (NO_X), and carbon dioxide (CO_2) emissions data and other information from power plants across the country as part of the Acid Rain Program (ARP), the Cross-State Air Pollution Rule (CSAPR), the CSAPR Update, and the Revised CSAPR Update (RCU). The CO_2 data from these Air Market Programs (AMP) can be compared to the electric power sector emissions calculated from the *Inventory* as shown in Table 3-18 for the three most recent years of data.

Table 3-18: Comparison of Electric Power Sector Emissions (MMT CO_2 Eq. and Percent)

Fuel/Sector	CO_2 Emissions (MMT CO_2 Eq.)			% Change	
	2020	2021	2022	20-21	21-22
Inventory Electric Power Sector	**1,439.6**	**1,540.9**	**1,531.7**	**7.0%**	**-0.6%**
Coal	788.2	910.1	851.5	15.5%	-6.4%
Natural Gas	634.8	612.8	659.3	-3.5%	7.6%
Petroleum	16.2	17.7	20.5	9.6%	15.9%
AMP Electric Power Sector	**1,430.8**	**1,531.7**	**1,520.1**	**7.1%**	**-0.8%**
Coal	792.7	913.4	858.5	15.2%	-6.0%
Natural Gas	629.4	609.6	652.7	-3.1%	7.1%
Petroleum	8.8	8.7	8.9	-0.8%	2.7%

Note: Totals may not sum due to independent rounding.

In general the emissions and trends from the two sources line up well. There are differences expected based on coverage and scope of each source. The *Inventory* covers all emissions from the electric power sector as defined above. The EPA AMP data covers emissions from electricity generating units of a certain size so in some respects it could cover more sources (like electric power units at industrial facilities that would be covered under the industrial sector in the *Inventory*) and not as many sources (since smaller units are excluded). The EPA AMP data also includes heat input for different fuel types. That data can be combined with emissions to calculate implied

emission factors.[45] The following Table 3-19 shows the implied emissions factors for coal and natural gas from the EPA AMP data compared to the factors used in the *Inventory* for the three most recent years of data.

Table 3-19: Comparison of Emissions Factors (MMT Carbon/QBtu)

Fuel Type	2020	2021	2022
EPA AMP			
Coal	25.67	25.66	25.53
Natural Gas	14.56	14.60	14.61
EPA Inventory			
Electric Power Coal	26.12	26.13	26.13
Natural Gas	14.43	14.43	14.43

The factors for natural gas line up reasonably well, the EPA factors are roughly 1 percent lower than those calculated from the EPA AMP data. For coal the EPA emissions factors are roughly 2 percent higher than those calculated from the EPA AMP data. One possible reason for the difference is that the EPA *Inventory* factors are based on all coal used in electric power production while the factors from the EPA AMP data are based on units where coal is the source of fuel used. There are units that use coal and other fuel sources but emissions for each fuel type could not be calculated. This is an area of further research but given current data available the approach to develop carbon factors as outlined in Annex 2 is still felt to be the most appropriate to represent total fuel combustion in the United States.

The Paris Agreement and the UNFCCC reporting guidelines also require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their “bottom-up” sectoral methodology. The reference approach (detailed in Annex 4) uses alternative methodologies and different data sources than those contained in this section of the report. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. In the reference approach, accounting for actual consumption of fuels at the sectoral or sub-national level is not required. One difference between the two approaches is that emissions from carbon that was not stored during non-energy use of fuels are subtracted from the sectoral approach and reported separately (see Section 3.2). These emissions, however, are not subtracted in the reference approach. As a result, the reference approach emission estimates are comparable to those of the sectoral approach, with the exception that the non-energy use (NEU) source category emissions are included in the reference approach (see Annex 4 for more details).

Recalculations Discussion

EIA (2024a) updated distillate fuel oil consumed by the transportation sector for 2010 and on. This caused transportation petroleum CO_2 emissions to increase by an average annual amount of 0.2 MMT CO_2 Eq. (less than half a percent) for the years 2010 through 2021.

EIA (2024a) updated propane consumed by the industrial sector for 2010 and on, which is used to calculate HGL (Energy Use) annually variable carbon content coefficients. In addition, EIA (2023b) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers. This change was made to reflect that natural gasoline and unfinished oils are used as feedstocks in crude oil production instead of directly consumed as an end-use fuel. EPA made the same adjustment across the timeseries. This change impacted industrial energy

[45] These emission factors can be converted from MMT Carbon/QBtu to MMT CO_2 Eq./QBtu by multiplying the emission factor by 44/12, the molecular-to-atomic weight ratio of CO_2 to C. This would assume the fraction oxidized to be 100 percent, which is the guidance in IPCC (2006) (see Annex 2.1).

consumption across the timeseries as well as non-energy use consumption, which impacts industrial energy consumption values. This change also impacted the HGL carbon content coefficient used to calculate emissions.

To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the total non-combustion consumption of HGLs as published by the EIA. Non-energy use consumption is subtracted from energy consumption, therefore this methodology change impacts industrial petroleum consumption values. Additionally, the energy HGL carbon contents are now calculated following the above methodology and have therefore increased across the timeseries, impacting U.S. Territories petroleum and industrial petroleum CO_2 emissions.

Overall, these four updates to EIA (2024a) data and methodology caused U.S. Territories petroleum CO_2 emissions to decrease by an average annual amount of less than 0.1 MMT CO_2 Eq. (less than half a percent) for the timeseries, and industrial petroleum CO_2 emissions to increase by an average annual amount of 5.0 MMT CO_2 Eq. (1.8 percent) for the timeseries.

EPA revised its calculation of change in total energy use in the industrial sector to include renewable energy and electricity. The value previously included only fossil fuel energy consumption. Additionally, EPA revised power sector carbon intensity data to correct for an error and ensure total renewable energy consumed from EIA's *Monthly Energy Review* (EIA 2024a) was being used. There were also very minor updates associated with changes in residential and commercial petroleum use due to MER updates changes in industrial coal use due to updated data on CO_2 exports.

Overall, these changes resulted in an average annual increase of 5.8 MMT CO_2 Eq. (0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2021, relative to the previous *Inventory*.

Planned Improvements

To reduce the uncertainty of CO_2 from fossil fuel combustion estimates for U.S. Territories, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from U.S. Territories. Additionally, although not technically a fossil fuel, since geothermal energy-related CO_2 emissions are included for reporting purposes, further expert elicitation may be conducted to better quantify the total uncertainty associated with CO_2 emissions from geothermal energy use.

EPA will continue to examine the availability of facility-level combustion emissions through EPA's GHGRP to help better characterize the industrial sector's energy consumption in the United States and further classify total industrial sector fossil fuel combustion emissions by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC methodologies, although for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the *Inventory* to estimate total national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the Paris Agreement and UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[46] In line with the Paris Agreement and UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from fossil fuel combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this *Inventory*.

Additional analyses will be conducted to align reported facility-level fuel types and IPCC fuel types per the national energy statistics. For example, additional work will look at CO_2 emissions from biomass to ensure they are

[46] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

separated in the facility-level reported data and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will continue to be relied upon.[47]

EPA is also evaluating the methods used to adjust for conversion of fuels and exports of CO_2. EPA is exploring the approach used to account for CO_2 transport, injection, and geologic storage; as part of this there may be changes made to the accounting for CO_2 exports.

Finally, another ongoing planned improvement is to evaluate data availability to update the carbon and heat content of more fuel types accounted for in this *Inventory*. This update will impact consumption and emissions across all sectors and will improve consistency with EIA data as carbon and heat contents of fuels will be accounted for as annually variable and therefore improve accuracy across the time series. Some of the fuels considered in this effort include petroleum coke, residual fuel, and woody biomass.

CH_4 and N_2O from Stationary Combustion

Methodology and Time-Series Consistency

Methane and N_2O emissions from stationary combustion were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type for industrial, residential, commercial, and U.S. Territories; and by fuel and technology type for the electric power sector). The electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology in accordance with IPCC methodological decision tree Figure 2.1 in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and available data. The activity data and emission factors used are described in the following subsections.

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

Industrial, Residential, Commercial, and U.S. Territories

National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, and U.S. Territories. For the CH_4 and N_2O emission estimates, consumption data for each fuel were obtained from EIA's *Monthly Energy Review* (EIA 2024a). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by EIA's International Energy Statistics (EIA 2024b).[48] Fuel consumption for the industrial sector was adjusted to subtract out mobile source construction and agricultural use, which is reported under mobile sources. Construction and agricultural mobile source fuel use was obtained from EPA (2022) and FHWA (1996 through 2023). Estimates for wood biomass consumption for fuel combustion do not include municipal solid waste, tires, etc., that are reported as biomass by EIA. Non-CO_2 emissions from combustion of the biogenic portion of municipal solid waste and tires is included under waste incineration (Section 3.2). Estimates for natural gas combustion do not include biogas, and therefore non-CO_2 emissions from biogas are not included (see the Planned Improvements section, below). Tier 1 default emission factors for the industrial, commercial, and residential end-use sectors were provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). U.S. Territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

Electric Power Sector

The electric power sector uses a Tier 2 emission estimation methodology as fuel consumption for the electric

[47] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[48] U.S. Territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

power sector by control-technology type is based on EPA's Acid Rain Program Dataset (EPA 2024). Total fuel consumption in the electric power sector from EIA (2024a) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2024) data. The combustion technology and fuel use data by facility obtained from EPA (2024) were only available from 1996 to 2022 so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2024) to the total EIA (2024a) consumption for each year from 1990 to 1995.

Emissions were estimated by multiplying fossil fuel and wood consumption by technology-, fuel-, and country-specific Tier 2 emission factors. The Tier 2 emission factors used are based in part on emission factors published by EPA, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for coal wall-fired boilers, residual fuel oil, diesel oil and wood boilers, natural gas-fired turbines, and combined cycle natural gas units.[49]

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022 as discussed below. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from biomass use in Territories, but those emissions are assumed to be insignificant.

Uncertainty

Methane emission estimates from stationary sources exhibit high uncertainty, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control).

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, with @RISK software.

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. About 55 input variables were simulated for the uncertainty analysis of this source category (about 20 from the CO_2 emissions from fossil fuel combustion inventory estimation model and about 35 from the stationary source inventory models).

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/EIA (2001) report.[50] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[51] However, the CH_4 emission factors differ from those used by EIA. These factors and uncertainty ranges are based on IPCC default uncertainty estimates (IPCC 2006).

[49] Several of the U.S. Tier 2 emission factors were used in IPCC (2006) as Tier 1 emission factors. See Table A-67 in Annex 3.1 for emission factors by technology type and fuel type for the electric power sector.

[50] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former distribution to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[51] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-20. Stationary combustion CH_4 emissions in 2022 (including biomass) were estimated to be between 5.9 and 19.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 31 percent below to 122 percent above the 2022 emission estimate of 8.6 MMT CO_2 Eq.[52] Stationary combustion N_2O emissions in 2022 (including biomass) were estimated to be between 16.5 and 33.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 33 percent below to 35 percent above the 2022 emission estimate of 24.7 MMT CO_2 Eq.

Table 3-20: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Energy-Related Stationary Combustion, Including Biomass (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH_4	8.6	5.9	19.1	-31%	122%
Stationary Combustion	N_2O	24.7	16.5	33.4	-33%	35%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

QA/QC and Verification

In order to ensure the quality of the non-CO_2 emission estimates from stationary combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH_4, N_2O, and the greenhouse gas precursors from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

Recalculations Discussion

EIA (2024a) updated industrial HGL statistics, which caused CH_4 and N_2O emissions from industrial fuel oil to decrease slightly for the years 2010 through 2021.

In addition, EIA (2023b) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers. This change was made to reflect the fact that these fuels are used as feedstocks in crude oil production instead of directly consumed as end-use fuels. EPA made the change across the time series. This change impacted energy consumption across the timeseries as well as non-energy use consumption, which impacts energy consumption values.

To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the

[52] The low emission estimates reported in this section have been rounded down to the nearest integer values and the high emission estimates have been rounded up to the nearest integer values.

total non-combustion consumption of HGLs as published by the EIA. Non-energy use consumption is subtracted from energy consumption, therefore this methodology change impacts industrial fuel oil consumption values.

Other small updates included changes in residential and commercial/institutional fuel oil are use and changes in industrial coal due to updated CO_2 export data.

Overall, these updates to EIA data and methodology (2024a) caused CH_4 and N_2O emissions from industrial fuel oil to increase by an average annual amount of 0.01 MMT CO_2 Eq. and 0.01 MMT CO_2 Eq. (3 percent and 3 percent), respectively, for the time series. EIA (2024a) updated 2020 and 2021 wood energy consumed by the residential sector due to new underlying data collected by the Residential Energy Consumption Survey (RECS), which collects data about once every 5 years and uses Annual Energy Outlook growth rates to estimate data for other years. This caused CH_4 and N_2O emissions from residential wood consumption to decrease by 0.76 MMT CO_2 Eq. and 0.10 MMT CO_2 Eq. (22 percent and 13 percent) in 2020, respectively, and 0.94 MMT CO_2 Eq. and 0.12 MMT CO_2 Eq. (26 percent and 15 percent) in 2021, respectively.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty for U.S. Territories. Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. Territories data. Because these data are not broken out by stationary and mobile uses, further research will be aimed at trying to allocate consumption appropriately. In addition, the uncertainty of biomass emissions will be further investigated because it was expected that the exclusion of biomass from the estimates would reduce the uncertainty; and in actuality the exclusion of biomass increases the uncertainty. These improvements are not all-inclusive but are part of an ongoing analysis and efforts to continually improve these stationary combustion estimates from U.S. Territories.

Other forms of biomass-based gas consumption include biogas. As an additional planned improvement, EPA will examine EIA and GHGRP data on biogas collected and burned for energy use and determine if CH_4 and N_2O emissions from biogas can be included in future Inventories. EIA (2024a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas.

CH_4 and N_2O from Mobile Combustion

Methodology and Time-Series Consistency

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for on-road vehicles and fuel consumption for non-road mobile sources. The activity data and emission factors used in the calculations are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle type, fuel type, model year, and emission control technology. Emission estimates for alternative fuel vehicles (AFVs) are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle and fuel type.[53]

[53] Alternative fuel and advanced technology vehicles are those that can operate using a motor fuel other than gasoline or diesel. This includes electric or other bi-fuel or dual-fuel vehicles that may be partially powered by gasoline or diesel.

CH_4 and N_2O emissions factors by vehicle type and emission tier for newer (starting with model year 2004) on-road gasoline vehicles were calculated by Browning (2019) from annual vehicle certification data compiled by EPA. CH_4 and N_2O emissions factors for older (model year 2003 and earlier) on-road gasoline vehicles were developed by ICF (2004). These earlier emission factors were derived from EPA, California Air Resources Board (CARB) and Environment and Climate Change Canada (ECCC) laboratory test results of different vehicle and control technology types. The EPA, CARB and ECCC tests were designed following the Federal Test Procedure (FTP). The procedure covers three separate driving segments, since vehicles emit varying amounts of greenhouse gases depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was then analyzed to determine quantities of gases present. The emissions characteristics of driving segment 2 tests were used to define running emissions. Running emissions were subtracted from the total FTP emissions to determine start emissions. These were then recombined to approximate average driving characteristics, based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts grams per mile emissions of CO_2, CO, HC, NO_x, and PM from vehicles under various conditions.[54]

Diesel on-road vehicle emission factors were developed by ICF (2006). CH_4 and N_2O emissions factors for newer (starting with model year 2007) on-road diesel vehicles (those using engine aftertreatment systems) were calculated from annual vehicle certification data compiled by EPA.

CH_4 and N_2O emission factors for AFVs were developed based on the 2022 Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (ANL 2022). For light-duty trucks, EPA used travel fractions for LDT1 and LDT2 (MOVES Source Type 31 for LDT1 and MOVES Source Type 32 for LDT2; see Annex 3.2 for information about the MOVES model) to determine emission factors. For medium-duty vehicles, EPA used emission factors for light heavy-duty vocational trucks. For heavy-duty vehicles, EPA used emission factors for long-haul combination trucks. For buses, EPA used emission factors for transit buses. These values represent vehicle operations only (tank-to-wheels); upstream well-to-tank emissions are calculated elsewhere in the Inventory. Biodiesel CH_4 emission factors were corrected from GREET values to be the same as CH_4 emission factors for diesel vehicles. GREET overestimated biodiesel CH_4 emission factors based upon an incorrect CH_4-to-THC ratio for diesel vehicles with aftertreatment technology.

Annual VMT data for 1990 through 2022 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2023). VMT estimates were then allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model (see Annex 3.2 for information about the MOVES model). This corrects time series inconsistencies in FHWA definitions of vehicle types (Browning 2022a). VMT for alternative fuel vehicles (AFVs) were estimated based on Browning (2022b). The age distributions of the U.S. vehicle fleet were obtained from EPA (2004, 2022), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2022).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 1998, 2022b, and 2023) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1994a, 1994b, 1998, 1999) and IPCC (2006) sources.

Non-Road Mobile Sources

The nonroad mobile category for CH_4 and N_2O includes ships and boats, aircraft, locomotives, and other mobile non-road sources (e.g., construction or agricultural equipment). For locomotives, aircraft, ships, and non-recreational boats, fuel-based emission factors are applied to data on fuel consumption, following the IPCC Tier 1 approach. The Tier 2 approach for these sources would require separate fuel-based emissions factors by

[54] Additional information regarding the MOBILE model can be found at https://www.epa.gov/moves/description-and-history-mobile-highway-vehicle-emission-factor-model.

technology, for which data are not currently available. For other non-road sources, EPA uses the Nonroad component of the MOVES model to estimate fuel use. Emission factors by horsepower bin are estimated from EPA engine certification data. Because separate emission factors are applied to specific engine technologies; these non-road sources utilize a Tier 2 approach.

To estimate CH_4 and N_2O emissions from non-road mobile sources, fuel consumption data were employed as a measure of activity and multiplied by fuel-specific emission factors (in grams of N_2O and CH_4 per kilogram of fuel consumed).[55] Activity data were obtained from AAR (2008 through 2023), APTA (2007 through 2023), Rail Inc (2014 through 2022), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), Bureau of Transportation Statistics (BTS; 2023), DLA Energy (2022), DOC (1991 through 2022), DOE (1993 through 2022), DOT (1991 through 2023), EIA (2002, 2007, 2023a, 2023b), EIA (1991 through 2022), EPA (2022), Esser (2003 through 2004), FAA (2024), FHWA (1996 through 2023),[56] Gaffney (2007), FTA (2023), and Whorton (2006 through 2014). Fuel consumption data for boats and vessels in U.S. Territories data and vessel domestic vessel bunkering is proxied from 2021 proxy data. Emission factors for non-road modes were taken from IPCC (2006) and Browning (2020 and 2018).

Uncertainty

A quantitative uncertainty analysis was conducted for the mobile source sector using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo stochastic simulation technique, using @RISK software. The uncertainty analysis was performed on 2022 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following four major sets of input variables: (1) VMT data, by on-road vehicle and fuel type, (2) emission factor data, by on-road vehicle, fuel, and control technology type, (3) fuel consumption, data, by non-road vehicle and equipment type, and (4) emission factor data, by non-road vehicle and equipment type.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched because emissions of these gases from motor vehicles are regulated in the United States, and the uncertainty in these emission estimates is believed to be relatively low. For more information, see Section 3.11. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors due to limited emission test data, and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

Based on the uncertainty analysis, mobile combustion CH_4 emissions from all mobile sources in 2022 were estimated to be between 2.5 and 3.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 4 percent below to 30 percent above the corresponding 2022 emission estimate of 2.6 MMT CO_2 Eq. Mobile combustion N_2O emissions from mobile sources in 2022 were estimated to be between 15.3 and 20.1MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 8 percent below to 20 percent above the corresponding 2022 emission estimate of 16.7 MMT CO_2 Eq.

[55] The consumption of international bunker fuels is not included in these activity data, but emissions related to the consumption of international bunker fuels are estimated separately under the International Bunker Fuels source category.

[56] This Inventory uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES model gasoline volumes to estimate non-road mobile source CH_4 and N_2O emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both non-road trucks and equipment. For construction and commercial/industrial category gasoline estimates, the 2014 and older MF-24 volumes represented non-road trucks only; therefore, the MOVES gasoline volumes for construction and commercial/industrial categories are added to the respective categories in the Inventory. Beginning in 2015, this addition is no longer necessary since the FHWA updated its methods for estimating on-road and non-road gasoline consumption. Among the method updates, FHWA now incorporates MOVES equipment gasoline volumes in the construction and commercial/industrial categories.

Table 3-21: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH_4	2.6	2.5	3.4	-4%	+30%
Mobile Sources	N_2O	16.7	15.3	20.1	-8%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Approach 2 uncertainty estimation methodology. As a result, as new information becomes available, uncertainty characterization of input variables may be improved and revised. For additional information regarding uncertainty in emission estimates for CH_4 and N_2O please refer to the Uncertainty Annex. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from any liquid fuel used in pipeline transport or some biomass used in transportation sources, but those emissions are assumed to be insignificant.

QA/QC and Verification

In order to ensure the quality of the emission estimates from mobile combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. The Tier 2 procedures focused on the emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emission estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between the current Inventory and the previous Inventory was also conducted to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

In previous *Inventories* (1990 through 2020 *Inventory* and before), on-highway greenhouse gas emissions were calculated using FHWA fuel consumption and vehicle miles traveled (VMT) data delineated by FHWA vehicle classes. These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from Oak Ridge National Laboratory's Transportation Energy Data Book (TEDB), to develop an estimate of fuel consumption for each vehicle type in the Inventory (i.e., passenger cars, light-duty trucks, buses, medium- and heavy-duty trucks, motorcycles). However, in 2011, FHWA changed its methods for estimating VMT and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated in the 1990 through 2008 *Inventory* and applied to the time series beginning in 2007. The FHWA methodology update resulted in large changes in VMT and fuel consumption by vehicle class, leading to a shift in emissions among vehicle classes. For example, FHWA replaced the vehicle category "Passenger Cars" with "Light-duty Vehicles-Short Wheelbase" and the "Other 2 axle-4 Tire Vehicles" category was replaced by "Light-duty Vehicles, Long Wheelbase." FHWA changed the definition of light-duty vehicles to less than 10,000 lbs. GVWR instead of 8,500 lbs. GVWR category updates pushed some single-unit heavy-duty trucks to the light-duty class. This change in vehicle classification also moved some smaller trucks and sport utility vehicles from the light truck category to the passenger cars category in this *Inventory*. These updates resulted in a disconnect in FHWA VMT and fuel consumption data in the 2006 to 2007 timeframe, generating a large drop in the light-duty truck VMT and fuel consumption trend lines between 2006 and 2007, and a corresponding increase in the passenger cars trend lines.

To address this inconsistency in the time series, EPA updated the methodology (starting with the 1990 through 2021 *Inventory*) to divide FHWA VMT data into vehicle classes and fuel type using distributions from EPA's *MOtor Vehicle Emission Simulator*, MOVES. The MOVES model is a nationally recognized model based on vehicle registration, travel activity, and emission rates that are updated with each model release. MOVES uses forecast growth factors which provide EPA's best estimate of likely future activity based on historical data (see Annex 3.2 for more information about the MOVES model). Thus, dividing FHWA total VMT data into vehicle class and fuel type using MOVES ratios provides a more consistent estimate of vehicle activity over the *Inventory* time series. MOVES ratios are also used to reallocate FHWA gasoline and diesel fuel use data (Browning 2022a). For this update, the MOVES3 model was run for calendar years 1990 and 1999 through 2022 for all vehicle types. Calendar years 1991 through 1998 were linearly interpolated from 1990 and 1999 calendar year MOVES3 outputs. Model outputs of VMT and fuel consumption were binned by calendar year, MOVES vehicle type, and fuel type; MOVES vehicle types were then mapped to the vehicle types used in the *Inventory*. Only outputs of gasoline and diesel fuel consumption from MOVES3 were used; alternative fuel VMT and fuel consumption outputs are ignored because they are calculated for the *Inventory* under a separate methodology. Total gasoline and diesel fuel consumption values from FHWA were then allocated to *Inventory* vehicle types using gasoline and diesel fuel consumption ratios by vehicle type from MOVES3. Similarly, VMT by vehicle type and fuel type was calculated by multiplying the total VMT from FHWA by VMT ratios by vehicle and fuel type generated by MOVES3. Overall, because total fuel consumption and VMT values are conserved, the changes in total emissions are small, within 0.1 percent. Observed differences in total emissions are due to changes in CH_4 and N_2O emissions, as the methodology for calculating these non-CO_2 emissions utilizes more detailed activity data and is therefore sensitive to the re-allocation of activity data. While total emissions estimates are not significantly impacted by this methodology update, there are significant changes in the allocation of emissions by vehicle type. The share of emissions allocated to passenger cars now generally decline through the time series while the share of emissions allocated to light-duty trucks increase over time.

In addition, the latest version of Argonne National Laboratory's *Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation Model (*GREET2022*)* provided updated emission factors for all alternative fuel vehicle classes (ANL 2022). Updated emission factors from GREET2022 were implemented in this *Inventory*, across the entire time series.

Additionally, new data from BTS on Amtrak fuel consumption for the time period 2019 through 2022 were included in this *Inventory* (BTS 2023).

Planned Improvements

While the data used for this report represent the most accurate information available, several areas for improvement have been identified.

- Update emission factors for ships and non-recreational boats using residual fuel and distillate fuel. Develop emission factors for locomotives using ultra-low sulfur diesel and emission factors for aircraft using jet fuel. The Inventory currently uses IPCC default values for these emission factors.
- Continue to explore potential improvements to estimates of domestic waterborne fuel consumption for future Inventories. The *Inventory* estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. Since 2015, all ships travelling within 200 nautical miles of the U.S. coastlines must use distillate fuels, thereby overestimating the residual fuel used by U.S. vessels and underestimating distillate fuel use in these ships. Additionally, the EIA has stopped publishing the Fuel Oil and Kerosene Sales report, which reported data on distillate marine fuel use in the U.S. and the territories. This affects the volume of fuel and emissions that are allocated to the domestic ships and boats source, although top-down data is still available from the Monthly Energy Review that will be used to estimate total domestic emission from diesel fuel use. New data and methods are being explored to improve the diesel ships and boats emissions estimates going forward.
- Update the analyses to use a forthcoming version of MOVES when it becomes available.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (CRT Source Category 1A)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses (NEU) in the United States. The fuels used for these purposes are diverse, including natural gas, hydrocarbon gas liquids (HGL),[57] asphalt (a viscous liquid mixture of heavy crude oil distillates), petroleum coke (manufactured from heavy oil), and coal (metallurgical) coke (manufactured from coking coal). The non-energy applications of these fuels are equally diverse, including feedstocks for the manufacture of plastics, rubber, synthetic fibers and other materials; reducing agents for the production of various metals and inorganic products; and products such as lubricants, waxes, and asphalt (IPCC 2006). Emissions from non-energy use of lubricants, paraffin waxes, bitumen/asphalt, and solvents are reported in the Energy sector, as opposed to the Industrial Processes and Product Use (IPPU) sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology (see Box 3-5). In addition, estimates of non-energy use emissions included here do not include emissions already reflected in the IPPU sector, e.g., fuels used as reducing agents. To avoid double counting, the "raw" non-energy fuel consumption data reported by EIA are reduced to account for these emissions already included under IPPU.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series and across all uses, about 64 percent of the total carbon consumed for non-energy purposes was stored in products (e.g., plastics), and not released to the atmosphere; the remaining 36 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of this *Inventory*. For example, some of the non-energy use products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the Incineration of Waste source category. There are also net exports of petrochemical intermediate products that are not completely accounted for in the EIA data, and the *Inventory* calculations adjust for the effect of net exports on the mass of carbon in non-energy applications.

As shown in Table 3-22, fossil fuel emissions in 2022 from the non-energy uses of fossil fuels were 102.8 MMT CO_2 Eq., which constituted approximately 2.0 percent of overall fossil fuel emissions. In 2022, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,428.2 TBtu (see Table 3-23). A portion of the carbon in the 5,428.2 TBtu of fuels was stored (236.7 MMT CO_2 Eq.), while the remaining portion was emitted (102.8 MMT CO_2 Eq.). Non-energy use emissions decreased by 7.9 percent from 2021 to 2022, primarily due to decreases in industrial coal, natural gas, and HGL fuel consumption. See Annex 2.3 for more details.

[57] HGL (formerly referred to as liquefied petroleum gas, or LPG) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures. HGLs include paraffins, such as ethane, propane, butanes, isobutane, and natural gasoline (formerly referred to as pentanes plus), and HGLs include olefins, such as ethylene, propylene, butylene and isobutylene.

Table 3-22: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO_2 Eq. and Percent C)

Year	1990	2005	2018	2019	2020	2021	2022
Potential Emissions	292.5	357.7	341.5	334.7	328.6	345.0	339.5
C Stored	193.4	232.7	223.2	228.2	230.8	233.4	236.7
Emissions as a % of Potential	34%	35%	35%	32%	30%	32%	30%
C Emitted	**99.1**	**125.0**	**118.4**	**106.5**	**97.8**	**111.6**	**102.8**

Note: NEU emissions presented in this table differ from the NEU emissions presented in CRT Table 1.A(a)s4 as the CRT NEU emissions do not include NEU of lubricants and other petroleum in U.S. Territories. NEU emissions from U.S. Territories are reported under U.S. Territories in the CRT Table 1.A(a)s4.

Methodology and Time-Series Consistency

As per discussion of methodology for estimating CO_2 emissions from fossil fuel combustion, NEU emissions are estimated in line with a Tier 2 method described by the *IPCC in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Chapter 2, Figure 2.1 decision tree and available data on energy use and country specific fuel carbon contents. The first step in estimating carbon stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The carbon content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific carbon content values. Both the non-energy fuel consumption and carbon content data were supplied by the EIA (2023) (see Annex 2.1). Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-23 and Table 3-24 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.[58] Consumption of natural gas, HGL, naphthas, other oils, and special naphtha were adjusted to subtract out net exports of these products that are not reflected in the raw data from EIA. Consumption values were also adjusted to subtract net exports of HGL components (e.g., propylene, ethane).

For the remaining non-energy uses, the quantity of carbon stored was estimated by multiplying the potential emissions by a storage factor.

- For several fuel types—petrochemical feedstocks (including natural gas for non-fertilizer uses, HGL, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on carbon stocks and flows were used to develop carbon storage factors, calculated as the ratio of (a) the carbon stored by the fuel's non-energy products to (b) the total carbon content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process and during use. Because losses associated with municipal solid waste management are handled separately in the Energy sector under the Incineration of Waste source category, the storage factors do not account for losses at the disposal end of the life cycle.
- For industrial coking coal and distillate fuel oil, storage factors were taken from Marland and Rotty (1984).
- For the remaining fuel types (petroleum coke, miscellaneous products and other petroleum), IPCC (2006) does not provide guidance on storage factors, and assumptions were made based on the potential fate of carbon in the respective non-energy use products. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke.

[58] These source categories include iron and steel production, lead production, zinc production, ammonia manufacture, carbon black manufacture (included in petrochemical production), titanium dioxide production, ferroalloy production, silicon carbide production, and aluminum production.

Table 3-23: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2018	2019	2020	2021	2022
Industry	**4,110.2**	**4,961.2**	**5,261.0**	**5,143.8**	**5,096.7**	**5,343.1**	**5,301.8**
Industrial Coking Coal	NO	80.4	124.7	112.8	79.9	77.9	46.7
Industrial Other Coal	7.6	11.0	9.5	9.5	9.5	9.5	9.5
Natural Gas to Chemical Plants	280.6	260.7	675.1	663.4	660.5	663.7	654.2
Asphalt & Road Oil	1,170.2	1,323.2	792.8	843.9	832.3	898.1	916.1
HGL[a]	1,135.0	1,554.3	2,427.6	2,372.8	2,469.5	2,639.0	2,758.8
Lubricants	186.3	160.2	122.0	118.3	111.1	113.5	119.5
Natural Gasoline[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Naphtha (<401 °F)	325.4	679.2	420.6	367.7	327.8	329.3	244.2
Other Oil (>401 °F)	660.4	499.2	218.8	211.1	194.7	195.3	111.1
Still Gas	36.7	67.7	166.9	158.7	145.4	152.8	157.1
Petroleum Coke	29.1	104.2	0.0	0.0	0.0	0.0	0.0
Special Naphtha	100.6	60.9	86.9	89.1	80.4	75.7	82.4
Distillate Fuel Oil	7.0	16.0	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	12.4	10.4	9.2	11.8	13.0
Miscellaneous Products	137.8	112.8	198.0	180.2	170.7	170.8	183.4
Transportation	**176.0**	**151.3**	**137.0**	**131.3**	**115.6**	**119.0**	**125.4**
Lubricants	176.0	151.3	137.0	131.3	115.6	119.0	125.4
U.S. Territories	**50.8**	**114.9**	**3.6**	**3.6**	**1.0**	**1.0**	**1.0**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	110.3	2.5	2.6	0.0	0.0	0.0
Total	**4,337.1**	**5,227.5**	**5,401.6**	**5,278.8**	**5,213.4**	**5,463.2**	**5,428.2**

NO (Not Occurring)

[a] Excludes natural gasoline.

[b] Formerly referred to as "pentanes plus." This source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.

Table 3-24: 2022 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (MMT C/QBtu)	Potential Carbon (MMT C)	Storage Factor (MMT C)	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO_2 Eq.)
Industry	**5,301.8**	**NA**	**90.0**	**NA**	**64.3**	**25.7**	**94.3**
Industrial Coking Coal	46.7	25.61	1.2	0.10	0.1	1.1	3.9
Industrial Other Coal	9.5	26.10	0.2	0.67	0.2	0.1	0.3
Natural Gas to Chemical Plants	654.2	14.47	9.4	0.67	6.3	3.1	11.4
Asphalt & Road Oil	916.1	20.55	18.8	1.00	18.7	0.1	0.3
HGL[b]	2,758.8	16.82	46.4	0.67	31.1	15.3	56.2
Lubricants	119.5	20.20	2.4	0.09	0.2	2.2	8.0
Natural Gasoline[c]	0.0	18.24	0.0	0.67	0.0	0.0	0.0
Naphtha (<401° F)	244.2	18.55	4.5	0.67	3.0	1.5	5.5
Other Oil (>401° F)	111.1	20.17	2.2	0.67	1.5	0.7	2.7
Still Gas	157.1	17.51	2.8	0.67	1.8	0.9	3.3
Petroleum Coke	0.0	27.85	0.0	0.30	0.0	0.0	0.0
Special Naphtha	82.4	19.74	1.6	0.67	1.1	0.5	2.0
Distillate Fuel Oil	5.8	20.22	0.1	0.50	0.1	0.1	0.2
Waxes	13.0	19.80	0.3	0.58	0.1	0.1	0.4
Miscellaneous Products	183.4	0.00	0.0	0.00	0.0	0.0	0.0
Transportation	**125.4**	**NA**	**2.5**	**NA**	**0.2**	**2.3**	**8.4**
Lubricants	125.4	20.20	2.5	0.09	0.2	2.3	8.4
U.S. Territories	**1.0**	**NA**	**+**	**NA**	**+**	**+**	**0.1**
Lubricants	1.0	20.20	+	0.09	+	+	0.1

Other Petroleum (Misc. Prod.)	+	20.00	+	0.10	+	+	+
Total	**5,428.2**		**92.6**		**64.6**	**28.0**	**102.8**

+ Does not exceed 0.05 TBtu, MMT C, or MMT CO_2 Eq.
NA (Not Applicable)
NO (Not Occurring)
[a] To avoid double counting, net exports have been deducted.
[b] Excludes natural gasoline.
[c] Formerly referred to as "pentanes plus." this source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.
Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the carbon stored from the potential emissions (see Table 3-22). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

Where storage factors were calculated specifically for the United States, data were obtained on (1) products such as asphalt, plastics, synthetic rubber, synthetic fibers, cleansers (soaps and detergents), pesticides, food additives, antifreeze and deicers (glycols), and silicones; and (2) industrial releases including energy recovery (waste gas from chemicals), Toxics Release Inventory (TRI) releases, hazardous waste incineration, and volatile organic compound, solvent, and non-combustion CO emissions. Data were taken from a variety of industry sources, government reports, and expert communications. Sources include EPA reports and databases such as compilations of air emission factors (EPA 2001), EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file (EPA 2023), *Toxics Release Inventory, 1998* (EPA 2000b), *Biennial Reporting System* (EPA 2000a, 2009), *Resource Conservation and Recovery Act Information System* (EPA 2013b, 2015, 2016b, 2018b, 2021), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011, 2017), and the Chemical Data Access Tool (EPA 2014b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013, 2017, 2021); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Census Bureau (1999, 2004, 2009, 2014, 2021); Bank of Canada (2012, 2013, 2014, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (2023); Gosselin, Smith, and Hodge (1984); EPA's *Municipal Solid Waste (MSW) Facts and Figures* (EPA 2013, 2014a, 2016a, 2018a, 2019); the U.S. Tire Manufacturers Association (USTMA 2012, 2013, 2014, 2016, 2018, 2020, 2022); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013); the Independent Chemical Information Service (ICIS 2008, 2016); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); the American Chemistry Council (ACC 2003 through 2011, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023a); the *Guide to the Business of Chemistry* (ACC 2023b); and the Chemistry Industry Association of Canada (CIAC 2023). Specific data sources are listed in full detail in Annex 2.3.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022 as discussed below.

Box 3-5: Reporting of Lubricants, Waxes, and Asphalt and Road Oil Product Use in Energy Sector

IPCC (2006) provides methodological guidance to estimate emissions from the first use of fossil fuels as a product for primary purposes other than combustion for energy purposes (including lubricants, paraffin waxes, bitumen / asphalt, and solvents) under the IPPU sector.[59] In this *Inventory*, carbon storage and carbon

[59] See for example Volume 3: Industrial Processes and Product Use, and Chapter 5: Non-Energy Products from Fuels and Solvent Use of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

emissions from product use of lubricants, waxes, and asphalt and road oil are reported under the Energy sector in the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category (CRT Source Category 1A5).[60]

The emissions are reported in the Energy sector, as opposed to the IPPU sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology. Although emissions from these non-energy uses are reported in the Energy chapter the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines*. The country-specific methodology used for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category is based on a carbon balance (i.e., carbon inputs-outputs) calculation of the aggregate amount of fossil fuels used for non-energy uses, including inputs of lubricants, waxes, asphalt and road oil (see Table 3-24).

For those inputs, U.S. country-specific data on carbon stocks and flows are used to develop carbon storage factors, which are calculated as the ratio of the carbon stored by the fossil fuel non-energy products to the total carbon content of the fuel consumed, taking into account losses in the production process and during product use.[61] The country-specific methodology to reflect national circumstances starts with the aggregate amount of fossil fuels used for non-energy uses and applies a carbon balance calculation, breaking out the carbon emissions from non-energy use of lubricants, waxes, and asphalt and road oil. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance and to avoid double counting. Due to U.S. national circumstances, reporting these carbon emissions separately under IPPU would involve making artificial adjustments to allocate both the carbon inputs and carbon outputs of the non-energy use carbon balance. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting these non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. To avoid presenting an incomplete carbon balance and a less transparent approach for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category calculation, the entire calculation of carbon storage and carbon emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology, and both the carbon storage and carbon emissions for lubricants, waxes, and asphalt and road oil are reported under the Energy sector.

However, emissions from non-energy uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, and zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances.

Uncertainty

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. This analysis, performed using @RISK software and the IPCC-recommended Approach 2 methodology (Monte Carlo stochastic simulation technique), provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the

[60] Non-methane volatile organic compound (NMVOC) emissions from solvent use are reported separately in the IPPU sector, following Chapter 5 of the *2006 IPCC Guidelines*.

[61] Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

inventory estimate. The results presented below provide the 95 percent confidence interval, the range of values within which emissions are likely to fall, for this source category.

As noted above, the non-energy use analysis is based on U.S.-specific storage factors for (1) feedstock materials (natural gas, HGL, natural gasoline, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2) asphalt, (3) lubricants, and (4) waxes. For the remaining fuel types (the "other" category in Table 3-23 and Table 3-24) the storage factors were taken directly from IPCC (2006), where available, and otherwise assumptions were made based on the potential fate of carbon in the respective NEU products. To characterize uncertainty, five separate analyses were conducted, corresponding to each of the five categories. In all cases, statistical analyses or expert judgments of uncertainty were not available directly from the information sources for all the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-25 (emissions) and Table 3-26 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2022 was estimated to be between 71.0 and 166.6 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 31 percent below to 62 percent above the 2022 emission estimate of 102.8 MMT CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

Table 3-25: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	81.4	51.7	146.6	-37%	+80%
Asphalt	CO_2	0.3	0.1	0.7	-58%	+119%
Lubricants	CO_2	16.6	13.7	19.2	-17%	+16%
Waxes	CO_2	0.4	0.3	0.7	-23%	+77%
Other	CO_2	4.2	0.8	4.9	-81%	+17%
Total	**CO_2**	**102.8**	**71.0**	**166.6**	**-31%**	**+62%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding.

Table 3-26: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2022 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	67.0%	52.3%	73.5%	-22%	+10%
Asphalt	CO_2	99.6%	99.1%	99.8%	0.5%	0.3%
Lubricants	CO_2	9.2%	3.9%	17.5%	-57%	+91%
Waxes	CO_2	57.8%	47.4%	67.5%	-18%	+17%
Other	CO_2	13.6%	8.1%	83.0%	-41%	+511%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, as a percentage of the inventory value (also expressed in percent terms).

As shown in Table 3-26, waxes and asphalt contribute least to overall storage factor uncertainty on a percentage basis. Although the feedstocks category—the largest use category in terms of total carbon flows—also appears to have relatively tight confidence limits, this is to some extent an artifact of the way the uncertainty analysis was structured. As discussed in Annex 2.3, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all of these fate processes, the current analysis addresses only the storage fates, and assumes that all carbon that is not stored is emitted. As the

production statistics that drive the storage values are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As is the case with the other uncertainty analyses discussed throughout this document, the uncertainty results above address only those factors that can be readily quantified. More details on the uncertainty analysis are provided in Annex 2.3.

QA/QC and Verification

In order to ensure the quality of the emission estimates from non-energy uses of fossil fuels, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. This effort included a general analysis, as well as portions of a category specific analysis for non-energy uses involving petrochemical feedstocks and for imports and exports. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology for estimating the fate of carbon (in terms of storage and emissions) across the various end-uses of fossil C. Emission and storage totals for the different subcategories were compared, and trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors and to improve the transparency of the calculations, facilitating future QA/QC.

For petrochemical import and export data, special attention was paid to NAICS numbers and titles to verify that none had changed or been removed. Import and export totals were compared with 2021 totals as well as their trends across the time series.

It is important to ensure no double counting of emissions between fuel combustion, non-energy use of fuels and industrial process emissions. For petrochemical feedstock production, our review of the categories suggests this is not a significant issue since the non-energy use industrial release data includes different categories of sources and sectors than those included in the Industrial Processes and Product Use (IPPU) emissions category for petrochemicals. Further data integration is not available at this time because feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. Also, GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers are unable to be used due to the data failing GHGRP CBI aggregation criteria. This country-specific approach taken is better able to reflect the national situation because it is accounting for secondary product imports and exports that are not included directly in the national energy statistics. Furthermore, it is compatible with the *2006 IPCC Guidelines* as discussed in Box 3-5 above, but also as the NEU emissions are here represent different emissions from those covered in the IPPU petrochemical production category.

Recalculations Discussion

Several updates to activity data factors lead to recalculations of previous year results. The major updates are as follows:

- U.S. International Trade Commission (2023) made changes to the classification of certain cleanser types, which doubled the historic emissions data for cleanser imports while exports remained constant.
- ACC (2023b) updated polyester, polyolefin and nylon fiber, ethylene glycol, maleic anhydride, adipic acid, and acetic acid production in 2021 which resulted in a slight decrease in emissions relative to the previous *Inventory*.
- U.S. International Trade Commission (2023) updated historical import and export data from 1996 to 2021, resulting in greater net exports relative to the previous *Inventory*.
- EIA (2024) shifted all 2022 product supplied of natural gasoline and unfinished oils to crude oil transfers, reflecting that, in actuality, nearly the full volume of these fuels is used as a feedstock in crude oil production, instead of directly consumed as an end-use fuel. Under EIA's guidance, EPA shifted all product supplied of natural gasoline to crude oil transfers for the time series. Natural gasoline was entirely

recategorized, which resulted in zero emissions for the time series from 1990 to 2022. Natural gasoline previously made up 1.7 percent of total emissions on average across the time series for non-energy uses of fossil fuels.

- To better align with EIA methodology, the non-energy use consumption of HGLs is now calculated for the entire timeseries by assuming that 100 percent of ethane, ethylene, and propylene consumption is for non-combustion use and 85 percent of normal butane, butylene, isobutane, and isobutylene is for non-combustion use. Non-energy use consumption of propane is calculated by subtracting the non-energy consumption of all other HGLs from the total non-combustion consumption of HGLs as published by the EIA. A further adjustment is made to natural gas, HGL, naphtha, other oil, and special naphtha consumption to account for exports of organic chemicals, cleansers, and pesticides. Because this adjustment is apportioned based on the relative ratios of each fuel, the emissions from these fuels have also changed slightly across the time series. Additionally, to better align with EIA methodology, the non-combustion and energy HGL carbon contents are now calculated for the entire timeseries following the above methodology. Overall, this update caused emissions from the non-energy use of natural gas to decrease an average of 27 MMT CO_2 Eq. annually, or 23 percent.

Overall, these changes resulted in an average annual decrease of 10.1 MMT CO_2 Eq. (8.2 percent) in carbon emissions from non-energy uses of fossil fuels for the period 1990 through 2021, relative to the previous *Inventory*.

Planned Improvements

There are several future improvements planned:

- More accurate accounting of carbon in petrochemical feedstocks. EPA has worked with EIA to determine the cause of input/output discrepancies in the carbon mass balance contained within the NEU model. In the future, two strategies to reduce or eliminate this discrepancy will continue to be pursued as part of quality control procedures. First, accounting of carbon in imports and exports will be improved. The import/export adjustment methodology will be examined to ensure that net exports of intermediaries such as ethylene and propylene are fully accounted for. Second, the use of top-down carbon input calculation in estimating emissions will be reconsidered. Alternative approaches that rely more substantially on the bottom-up carbon output calculation will be considered instead.
- Improving the uncertainty analysis. Most of the input parameter distributions are based on professional judgment rather than rigorous statistical characterizations of uncertainty.
- Better characterizing flows of fossil carbon. Additional fates may be researched, including the fossil carbon load in organic chemical wastewaters, plasticizers, adhesives, films, paints, and coatings. There is also a need to further clarify the treatment of fuel additives and backflows (especially methyl tert-butyl ether, MTBE).
- Reviewing the trends in fossil fuel consumption for non-energy uses. Annual consumption for several fuel types is highly variable across the time series, including industrial coking coal and other petroleum. A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses.
- Updating the average carbon content of solvents was researched, since the entire time series depends on one year's worth of solvent composition data. The data on carbon emissions from solvents that were readily available do not provide composition data for all categories of solvent emissions and also have conflicting definitions for volatile organic compounds, the source of emissive carbon in solvents. Additional sources of solvents data will be investigated in order to update the carbon content assumptions.
- Updating the average carbon content of cleansers (soaps and detergents) was researched; although production and consumption data for cleansers are published every 5 years by the Census Bureau, the composition (C content) of cleansers has not been recently updated. Recently available composition data

sources may facilitate updating the average carbon content for this category.

- Revising the methodology for consumption, production, and carbon content of plastics was researched; because of recent changes to the type of data publicly available for plastics, the NEU model for plastics applies data obtained from personal communications. Potential revisions to the plastics methodology to account for the recent changes in published data will be investigated.
- Although U.S.-specific storage factors have been developed for feedstocks, asphalt, lubricants, and waxes, default values from IPCC are still used for two of the non-energy fuel types (industrial coking coal, distillate oil), and broad assumptions are being used for miscellaneous products and other petroleum. Over the long term, there are plans to improve these storage factors by analyzing carbon fate similar to those described in Annex 2.3 or deferring to more updated default storage factors from IPCC where available.
- Reviewing the storage of carbon black across various sectors in the *Inventory*; in particular, the carbon black abraded and stored in tires.
- Assess the current method and/or identify new data sources (e.g., EIA) for estimating emissions from ammonia/fertilizer use of natural gas.
- Investigate EIA NEU and MECS data to update, as needed, adjustments made for ammonia production and "natural gas to chemical plants, other uses" and "natural gas to other" non-energy uses, including iron and steel production, in energy uses and IPPU.

3.3 Incineration of Waste (CRT Source Category 1A)

Combustion is used to manage about 7 to 19 percent of the solid wastes generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000; EPA 2020; Goldstein and Madtes 2001; Kaufman et al. 2004; Simmons et al. 2006; van Haaren et al. 2010). In the context of this section, waste includes all municipal solid waste (MSW) as well as scrap tires. In the United States, combustion of MSW tends to occur at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste combustion are accounted for in the Energy chapter. Similarly, scrap tires are combusted for energy recovery in industrial and utility boilers, pulp and paper mills, and cement kilns. Combustion of waste results in conversion of the organic inputs to CO_2. According to the *2006 IPCC Guidelines*, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon derived from fossil sources.

Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net carbon flows accounted for under the Land Use, Land-Use Change, and Forestry chapter. However, some components of MSW and scrap tires—plastics, synthetic rubber, synthetic fibers, and carbon black—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. As noted above, scrap tires (which contain synthetic rubber and carbon black) are also considered a "non-hazardous" waste and are included in the waste combustion estimate, though waste disposal practices for tires differ from MSW. Estimates on emissions from hazardous waste combustion can be found in Annex 2.3 and are accounted for as part of the carbon mass balance for non-energy uses of fossil fuels.

Approximately 26.3 million metric tons of MSW were combusted in 2022 (EPA 2022). Carbon dioxide emissions from combustion of waste decreased 4.2 percent since 1990, to an estimated 12.4 MMT CO_2 (12,357 kt) in 2022. Emissions across the time series are shown in Table 3-27 and Table 3-28.

Waste combustion is also a source of CH_4 and N_2O emissions (De Soete 1993; IPCC 2006). Methane emissions from the combustion of waste were estimated to be less than 0.05 MMT CO_2 Eq. (less than 0.05 kt CH_4) in 2022 and have remained steady since 1990. Nitrous oxide emissions from the combustion of waste were estimated to be 0.3 MMT CO_2 Eq. (1.3 kt N_2O) in 2022 and have decreased by 18 percent since 1990. This decrease is driven by the decrease in total MSW combusted.

Table 3-27: CO_2, CH_4, and N_2O Emissions from the Combustion of Waste (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	12.9	13.3	13.3	12.9	12.9	12.5	12.4
CH_4	+	+	+	+	+	+	+
N_2O	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Total	**13.3**	**13.6**	**13.7**	**13.3**	**13.3**	**12.8**	**12.7**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 3-28: CO_2, CH_4, and N_2O Emissions from the Combustion of Waste (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	12,900	13,254	13,339	12,948	12,921	12,476	12,357
CH_4	+	+	+	+	+	+	+
N_2O	2	1	1	1	1	1	1

+ Does not exceed 0.05 kt.

Methodology and Time-Series Consistency

Municipal Solid Waste Combustion

To determine both CO_2 and non-CO_2 emissions from the combustion of waste, the tonnage of waste combusted and an estimated emissions factor are needed. Emission estimates from the combustion of tires are discussed separately. Data for total waste combusted was derived from *BioCycle* (van Haaren et al. 2010), EPA Facts and Figures Report, Energy Recovery Council (ERC), EPA's Greenhouse Gas Reporting Program (GHGRP), and the U.S. Energy Information Administration (EIA). Multiple sources were used to ensure a complete, quality dataset, as each source encompasses a different timeframe.

EPA determined the MSW tonnages based on data availability and accuracy throughout the time series.

- 1990-2006: MSW combustion tonnages are from Biocycle combustion data. Tire combustion data from the U.S. Tire Manufacturers Association (USTMA) are removed to arrive at MSW combusted without tires.
- 2006-2010: MSW combustion tonnages are an average of Biocycle (with USTMA tire data tonnage removed), U.S. EPA Facts and Figures, EIA, and Energy Recovery Council data (with USTMA tire data tonnage removed).
- 2011-2022: MSW combustion tonnages are from EPA's GHGRP data.

Table 3-29 provides the estimated tons of MSW combusted including and excluding tires.

Table 3-29: Municipal Solid Waste Combusted (Short Tons)

	1990	2005	2018	2019	2020	2021	2022
Waste Combusted *(excluding tires)*	33,344,839	26,486,414	29,162,364	28,174,311	27,586,271	27,867,446	26,338,130
Waste Combusted *(including tires)*	33,766,239	28,631,054	30,853,949	29,821,141	29,106,686	29,261,446	27,732,130

Sources: BioCycle, EPA Facts and Figures, ERC, GHGRP, EIA, USTMA.

CO_2 Emissions from MSW Excluding Scrap Tires

Fossil CO_2 emission factors were calculated from EPA's GHGRP data for non-biogenic sources. Using GHGRP-reported emissions for CH_4 and N_2O and assumed emission factors, the tonnage of waste combusted, excluding tires, was derived. Methane and N_2O emissions and assumed emission factors were used to estimate the amount of MSW combusted in terms of energy content. The energy content of MSW combusted was then converted into tonnage based on assumed MSW heating value. Two estimates were generated (one for CH_4 and one for N_2O) and the two were averaged together. Dividing fossil CO_2 emissions from GHGRP FLIGHT data for MSW combustors by this estimated tonnage yielded an annual CO_2 emission factor. As this data was only available following 2011, all years prior use an average of the emission factors from 2011 through 2015. See Annex 3.7 for more detail on how MSW carbon factors were calculated.

Finally, CO_2 emissions were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated fossil CO_2 emission factors are shown in Table 3-30.

Table 3-30: Calculated Fossil CO_2 Content per Ton Waste Combusted (kg CO_2/Short Ton Combusted)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Emission Factors	366	366	361	363	377	365	382

CO_2 Emissions from Scrap Tires

Scrap tires contain several types of synthetic rubber, carbon black, and synthetic fibers. Each type of synthetic rubber has a discrete carbon content, and carbon black is 100 percent C. For synthetic rubber and carbon black in scrap tires, information on average weight, disposal percentage, and total tires incinerated for energy was obtained biannually from U.S. Scrap Tire Management Summary for 2005 through 2022 data (USTMA 2022). Information about scrap tire composition was taken from the Rubber Manufacturers' Association internet site (USTMA 2012a). Emissions of CO_2 were calculated based on the amount of scrap tires used for fuel and the synthetic rubber and carbon black content of scrap tires. The mass of combusted material is multiplied by its carbon content to calculate the total amount of carbon stored. 2022 values are proxied from 2021 data. More detail on the methodology for calculating emissions from each of these waste combustion sources is provided in Annex 3.7. Table 3-31 provides CO_2 emissions from combustion of waste tires.

Table 3-31: CO_2 Emissions from Combustion of Tires (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Synthetic Rubber	0.3	1.6	1.3	1.2	1.1	1.0	1.0
C Black	0.4	2.0	1.5	1.5	1.4	1.3	1.3
Total	**0.7**	**3.6**	**2.8**	**2.7**	**2.5**	**2.3**	**2.3**

Non-CO_2 Emissions

Combustion of waste also results in emissions of CH_4 and N_2O. These emissions were calculated by multiplying the total estimated mass of waste combusted, including tires, by the respective emission factors. The emission factors for CH_4 and N_2O emissions per quantity of MSW combusted are default emission factors for the default continuously-fed stoker unit MSW combustion technology type and were taken from IPCC (2006).

Uncertainty

An Approach 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO_2 emissions and N_2O emissions from the incineration of waste (given the very low emissions for CH_4, no uncertainty estimate was derived). IPCC Approach 2 analysis allows the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for most variables; thus, uncertainty estimates for these variables were determined using assumptions based on source category knowledge and the known uncertainty estimates for the waste generation variables.

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include reported CO_2 emissions; N_2O and CH_4 emissions factors, and tire synthetic rubber and black carbon contents. The highest levels of uncertainty surround the reported emissions from GHGRP; the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, carbon content of carbon black).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-32. Waste incineration CO_2 emissions in 2022 were estimated to be between 10.3 and 14.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 17 percent below to 16 percent above the 2022 emission estimate of 12.4 MMT CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2022 were estimated to be between 0.2 and 0.9 MMT CO_2 Eq. This indicates a range of 54 percent below to 164 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq.

Table 3-32: Approach 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	12.4	10.3	14.4	-17%	16%
Incineration of Waste	N_2O	0.3	0.2	0.9	-54%	164%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates from waste combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and specifically focused on the emission factor and activity data sources and methodology used for estimating emissions from combustion of waste. Trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors in the use of activity data.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

Research was conducted to review the composition of carbon black abraded and stored in tires. No definitive sources were found that support updating the current factor of 28 percent carbon black for commercial and light duty tires. This factor was not updated, but additional research can be completed in future *Inventory* cycles.

3.4 Coal Mining (CRT Source Category 1B1a)

Three types of coal mining-related activities release CH_4 and CO_2 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. While surface coal mines account for the majority of U.S. coal production, underground coal mines contribute the largest share of fugitive CH_4 emissions (see Table 3-34 and Table 3-35) due to the higher CH_4 content of coal in the deeper underground coal seams. In 2022, 185 underground coal mines and 354 surface mines were operating in the United States (EIA 2023). In recent years, the total number of active coal mines in the United States has declined. In 2022, the United States was the fourth largest coal producer in the world, after China, India, and Indonesia (IEA 2022).

Table 3-33: Coal Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Underground							
Number of Mines	1,683	586	236	226	196	174	185
Production	384,244	334,399	249,804	242,557	177,380	200,122	201,525
Surface							
Number of Mines	1,656	789	430	432	350	332	354
Production	546,808	691,447	435,521	397,750	307,944	323,142	336,990
Total							
Number of Mines	**3,339**	**1,398**	**666**	**658**	**546**	**506**	**539**
Production	**931,052**	**1,025,846**	**685,325**	**640,307**	**485,324**	**523,264**	**538,515**

Fugitive CH_4 Emissions

Underground coal mines liberate CH_4 from ventilation systems and from degasification systems. Ventilation systems pump air through the mine workings to dilute noxious gases and ensure worker safety; these systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large, often highly concentrated volumes of CH_4 before, during, or after mining. Some mines recover and use CH_4 generated from ventilation and degasification systems, thereby reducing emissions to the atmosphere.

Surface coal mines liberate CH_4 as the overburden is removed and the coal is exposed to the atmosphere. Methane emissions are normally a function of coal rank (a classification related to the percentage of carbon in the coal) and depth. Surface coal mines typically produce lower-rank coals and remove less than 250 feet of overburden, so their level of emissions is much lower than from underground mines.

In addition, CH_4 is released during post-mining activities, as the coal is processed, transported, and stored for use.

Total CH_4 emissions in 2022 were estimated to be 1,558 kt (43.6 MMT CO_2 Eq.), a decline of approximately 60 percent since 1990 (see Table 3-34 and Table 3-35). In 2022, underground mines accounted for approximately 72 percent of total emissions, surface mines accounted for 14 percent, and post-mining activities accounted for 14 percent. In 2022, total CH_4 emissions from coal mining decreased by approximately 2 percent relative to the previous year. Total coal production in 2022 increased by 3 percent compared to 2021. This resulted in an increase of 4 percent in CH_4 emissions from surface mining and post-mining activities in 2022. However, surface mining and post-mining activities have a lower impact on total CH_4 compared to underground mining (72 percent of total emissions in 2022). The number of operating underground mines increased in 2022 and the amount of CH_4 recovered and used in 2022 increased by 25 percent compared to 2021. This resulted in a slight decrease in overall CH_4 emissions in 2022 (2 percent), compared to 2021.

Table 3-34: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**83.1**	**46.7**	**43.6**	**38.5**	**35.2**	**32.9**	**31.5**
Liberated	90.6	66.9	66.7	56.6	53.7	52.3	55.7
Recovered & Used	(7.5)	(20.1)	(23.1)	(18.1)	(18.5)	(19.4)	(24.2)
Surface Mining	**12.0**	**13.3**	**7.8**	**7.2**	**5.4**	**5.7**	**6.0**
Post-Mining (UG)	**10.3**	**8.6**	**5.9**	**5.8**	**4.3**	**4.8**	**4.8**
Post-Mining (Surface)	**2.6**	**2.9**	**1.7**	**1.5**	**1.2**	**1.2**	**1.3**
Total	**108.1**	**71.5**	**59.1**	**53.0**	**46.2**	**44.7**	**43.6**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-35: CH_4 Emissions from Coal Mining (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**2,968**	**1,669**	**1,557**	**1,375**	**1,257**	**1,176**	**1,124**
Liberated	3,237	2,388	2,382	2,022	1,917	1,868	1,989
Recovered & Used	(269)	(720)	(825)	(646)	(660)	(692)	(865)
Surface Mining	**430**	**475**	**280**	**255**	**194**	**205**	**215**
Post-Mining (UG)	**368**	**306**	**212**	**206**	**155**	**170**	**173**
Post-Mining (Surface)	**93**	**103**	**61**	**55**	**42**	**44**	**47**
Total	**3,860**	**2,552**	**2,110**	**1,892**	**1,648**	**1,595**	**1,558**

Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 3 method for estimating CH_4 emissions from underground coal mining and an IPCC Tier 2 method for estimating CH_4 emissions from surface mining and post-mining activities (for coal production from both underground mines and surface mines) in accordance with methodological decisions trees in IPCC guidelines (Volume 2, Chapter 4, Figure 4.1.1 and 4.1.2) and available data (IPCC 2006). The methodology for estimating CH_4 emissions from coal mining consists of two steps:

- Estimate CH_4 emissions from underground mines. These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH_4 liberated. The CH_4 recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- Estimate CH_4 emissions from surface mines and post-mining activities. Unlike the methodology for underground mines, which uses mine-specific data, the methodology for estimating emissions from surface mines and post-mining activities consists of multiplying basin-specific coal production by basin-specific gas content and an emission factor.

Step 1: Estimate CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and degasification systems. Some mines recover and

use the liberated CH_4, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus the CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

To estimate CH_4 liberated from ventilation systems, EPA uses data collected through its Greenhouse Gas Reporting Program (GHGRP)[62] (Subpart FF, "Underground Coal Mines"), data provided by the U.S. Mine Safety and Health Administration (MSHA) (MSHA 2023), and occasionally data collected from other sources on a site-specific level (e.g., state gas production databases). Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2023).[63] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems; they have the option of recording and reporting their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the United States with detectable CH_4 concentrations.[64]

Since 2013, ventilation CH_4 emission estimates have been calculated based on both quarterly GHGRP data submitted by underground mines and on quarterly measurement data obtained directly from MSHA. Because not all mines report under EPA's GHGRP, the emissions of the mines that do not report must be calculated using MSHA data. The MSHA data also serves as a quality assurance tool for validating GHGRP data. For GHGRP data, reported quarterly ventilation methane emissions (metric tons) are summed for each mine to develop mine-specific annual ventilation emissions. For MSHA data, the average daily CH_4 emission rate for each mine is determined using the CH_4 total for all data measurement events conducted during the calendar year and total duration of all data measurement events (in days). The calculated average daily CH_4 emission rate is then multiplied by 365 days to estimate annual ventilation CH_4 emissions for the MSHA dataset.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Particularly gassy underground mines also use degasification systems (e.g., wells or boreholes) to remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Nineteen mines used degasification systems in 2022 and all of these mines reported the CH_4 removed through these systems to EPA's GHGRP under Subpart FF (EPA 2023). Based on the weekly measurements reported to EPA's GHGRP, degasification data summaries for each mine are added to estimate the CH_4 liberated from degasification systems. Twelve of the 19 mines with degasification systems had operational CH_4 recovery and use projects, including two mines with two recovery and use projects each (see step 1.3 below).[65]

Degasification data reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate CH_4 liberated from degasification systems at 13 of the 19 mines that used degasification systems in 2022. Data from state gas well production databases were used to supplement GHGRP degasification data for the remaining six mines (DMME 2023; GSA 2023; WVGES 2023; McElroy OVS 2013).

---

[62] In implementing improvements and integrating data from EPA's GHGRP, EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

[63] Underground coal mines report to EPA under Subpart FF of the GHGRP (40 CFR Part 98). In 2022, 61 underground coal mines reported to the program.

[64] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

[65] Several of the mines venting CH_4 from degasification systems use a small portion of the gas to fuel gob well blowers in remote locations where electricity is not available. However, this CH_4 use is not considered to be a formal recovery and use project.

For pre-mining wells, cumulative degasification volumes that occur prior to the well being mined through are attributed to the mine in the inventory year in which the well is mined through.[66] EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under Subpart FF.[67] Most pre-mining wells drilled from the surface are considered coalbed methane wells prior to mine-through and associated CH_4 emissions are reported under another subpart of the GHGRP (Subpart W, "Petroleum and Natural Gas Systems"). As a result, GHGRP data must be supplemented to estimate cumulative degasification volumes that occurred prior to well mine-through. There were four mines with degasification systems that include pre-mining wells that were mined through in 2022. For all of these mines, GHGRP data were supplemented with historical data from state gas well production databases (ERG 2023; GSA 2023), as well as with mine-specific information regarding the locations and dates on which the pre-mining wells were mined through (JWR 2010; El Paso 2009; ERG 2023).

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Twelve mines had a total of fourteen CH_4 recovery and use projects in place in 2022, including two mines that each have two recovery and use projects. Thirteen of these projects involved degasification systems with one mine having a ventilation air methane abatement project (VAM). Eleven of these mines sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. One mine destroyed the recovered CH_4 (VAM) using regenerative thermal oxidation (RTO) without energy recovery and using enclosed flares.

The CH_4 recovered and used (or destroyed) at the twelve mines described above are estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from six of the 12 mines that deployed degasification systems in 2022. Based on quarterly measurements, the GHGRP degasification destruction data summaries for each mine are added together to estimate the CH_4 recovered and used from degasification systems.
- State sales data were used to supplement GHGRP data to estimate CH_4 recovered and used from five mines that deployed degasification systems in 2022 (DMME 2023, ERG 2023, GSA 2023, and WVGES 2023). Four of these mines intersected pre-mining wells in 2022. Supplemental information is used for these mines because estimating CH_4 recovery and use from pre-mining wells requires additional data not reported under Subpart FF of EPA's GHGRP (see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The supplemental data is obtained from state gas production databases as well as mine-specific information on the location and timing of mined-through pre-mining wells.
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2023). This mine also reported CH_4 reductions from flaring. GHGRP data were used to estimate CH_4 recovered and flared in 2022.

Step 2: Estimate CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH_4 emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* (EIA 2023) is multiplied by basin-specific CH_4 contents (EPA 1996, 2005) and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions (King 1994; Saghafi

[66] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

[67] This applies for pre-drainage in years prior to the well being mined through. Beginning with the year the well is mined through, the annual volume of CH_4 liberated from a pre-drainage well is reported under Subpart FF of EPA's GHGRP.

2013). For post-mining activities, basin-specific coal production is multiplied by basin-specific CH_4 contents and a mid-range 32.5 percent emission factor for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific in situ gas content data were compiled from AAPG (1984) and USBM (1986).

Fugitive CO_2 Emissions

Methane and CO_2 are naturally occurring in coal seams and are collectively referred to as coal seam gas. These gases remain trapped in the coal seam until coal is mined (i.e., coal seam is exposed and fractured during mining operations). Fugitive CO_2 emissions occur during underground coal mining, surface coal mining, and post-mining activities. Methods and data to estimate fugitive CO_2 emissions from underground and surface coal mining are presented in the sections below. Fugitive CO_2 emissions from post-mining activities were not estimated due to the lack of an IPCC method and unavailability of data.

Total fugitive CO_2 emissions in 2022 were estimated to be 2,474 kt (2.5 MMT CO_2 Eq.), a decline of approximately 46 percent since 1990. In 2022, underground mines accounted for approximately 89 percent of total fugitive CO_2 emissions. In 2022, total fugitive CO_2 emissions from coal mining increased by approximately 1 percent relative to the previous year. This increase was due to an increase in annual coal production.

Table 3-36: CO_2 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**4.2**	**3.6**	**2.8**	**2.7**	**1.9**	**2.2**	**2.2**
Liberated	4.2	3.6	2.7	2.6	1.9	2.2	2.2
Recovered & Used	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Flaring	NO	NO	0.1	0.1	+	+	+
Surface Mining	**0.4**	**0.6**	**0.4**	**0.3**	**0.2**	**0.3**	**0.3**
Total	**4.6**	**4.2**	**3.1**	**3.0**	**2.2**	**2.5**	**2.5**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-37: CO_2 Emissions from Coal Mining (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**4,164**	**3,610**	**2,787**	**2,670**	**1,948**	**2,193**	**2,201**
Liberated	4,171	3,630	2,712	2,633	1,926	2,173	2,188
Recovered & Used	(8)	(21)	(23)	(18)	(19)	(19)	(24)
Flaring	NO	NO	97	55	41	40	38
Surface Mining	**443**	**560**	**353**	**322**	**249**	**262**	**273**
Total	**4,606**	**4,169**	**3,139**	**2,992**	**2,197**	**2,455**	**2,474**

NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 1 method for estimating fugitive CO_2 emissions from underground coal mining and surface mining in accordance with methodological decisions trees in IPCC guidelines (Volume 2, Chapter 4, Figure 4.1.1a) and available data (IPCC 2019). IPCC methods and data to estimate fugitive CO_2 emissions from post-mining activities (for both underground and surface coal mining) are currently not available.

Step 1: Underground Mining

EPA used the following overarching IPCC equation to estimate fugitive CO_2 emissions from underground coal mines (IPCC 2019):

Equation 3-1: Estimating Fugitive CO_2 Emissions from Underground Mines

$$Total\ CO_2\ from\ Underground\ Mines = CO_2\ from\ underground\ mining\ - Amount\ of\ CO_2\ in\ gas\ recovered + CO_2\ from\ methane\ flaring$$

Step 1.1: Estimate Fugitive CO_2 Emissions from Underground Mining

EPA estimated fugitive CO_2 emissions from underground mining using the IPCC Tier 1 emission factor (5.9 m^3/metric ton) and annual coal production from underground mines (EIA 2023). The underground mining default emission factor accounts for all the fugitive CO_2 likely to be emitted from underground coal mining. Therefore, the amount of CO_2 from coal seam gas recovered and utilized for energy is subtracted from underground mining estimates in Step 2, below. Under IPCC methods, the CO_2 emissions from gas recovered and utilized for energy use (e.g., injected into a natural gas pipeline) are reported under other sectors of the *Inventory* (e.g., stationary combustion of fossil fuel or oil and natural gas systems) and not under the coal mining sector.

Step 1.2: Estimate Amount of CO_2 In Coal Seam Gas Recovered for Energy Purposes

EPA estimated fugitive CO_2 emissions from coal seam gas recovered and utilized for energy purposes by using the IPCC Tier 1 default emission factor (19.57 metric tons CO_2/million cubic meters of coal bed methane (CBM) produced) and quantity of coal seam gas recovered and utilized. Data on annual quantity of coal seam gas recovered and utilized are available from GHGRP and state sales data (GHGRP 2023; DMME 2023; ERG 2023; GSA 2023; WVGES 2023). The quantity of coal seam gas recovered and destroyed without energy recovery (e.g., VAM projects with RTO) is deducted from the total coal seam gas recovered quantity (McElroy OVS 2023).

Step 1.3: Estimate Fugitive CO_2 Emissions from Flaring

The IPCC method includes combustion CO_2 emissions from gas recovered for non-energy uses (i.e., flaring, or catalytic oxidation) under fugitive CO_2 emission estimates for underground coal mining. In effect, these emissions, though occurring through stationary combustion, are categorized as fugitive emissions in the *Inventory*. EPA estimated CO_2 emissions from methane flaring using the following equation:

Equation 3-2: Estimating CO_2 Emissions from Drained Methane Flared or Catalytically Oxidized

$$CO_2\ from\ flaring = 0.98 \times Volume\ of\ methane\ flared \times Conversion\ Factor \times Stoichiometric\ Mass\ Factor$$

Currently there are three mines that report destruction of recovered methane through flaring without energy use. Annual data for 2022 were obtained from one mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) and the GHGRP for the remaining two mines (McElroy OVS 2023; GHGRP 2023).

Step 2: Surface Mining

EPA estimated fugitive CO_2 emissions from surface mining using the IPCC Tier 1 emission factor (0.44 m^3/metric ton) and annual coal production from surface mines (EIA 2023).

Uncertainty

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. Because emission estimates of CH_4 from underground ventilation systems were based on actual measurement data from EPA's GHGRP or from MSHA, uncertainty is relatively low. A degree of imprecision was introduced because the ventilation air measurements

used were not continuous but rather quarterly instantaneous readings that were used to determine the average annual emission rates. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky & Wang 2000). Equipment measurement uncertainty is applied to GHGRP data.

Estimates of CH_4 liberated and recovered by degasification systems are relatively certain for utilized CH_4 because of the availability of EPA's GHGRP data and state gas sales information. Many of the liberation and recovery estimates use data on wells within 100 feet of a mined area. However, uncertainty exists concerning the radius of influence of each well. The number of wells counted, and thus the liberated CH_4 and avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

EPA's GHGRP requires weekly CH_4 monitoring of mines that report degasification systems, and continuous CH_4 monitoring is required for CH_4 utilized on- or off-site. Since 2012, GHGRP data have been used to estimate CH_4 emissions from vented degasification wells, reducing the uncertainty associated with prior MSHA estimates used for this sub-source. Beginning in 2013, GHGRP data were also used for determining CH_4 recovery and use at mines without publicly available gas usage or sales records, which has reduced the uncertainty from previous estimation methods that were based on information from coal industry contacts.

Surface mining and post-mining emissions are associated with considerably more uncertainty than underground mines, because of the difficulty in developing accurate emission factors from field measurements. However, since underground coal mining, as a general matter, results in significantly larger CH_4 emissions due to production of higher-rank coal and greater depth, and estimated emissions from underground mining constitute the majority of estimated total coal mining CH_4 emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty.

The major sources of uncertainty for estimates of fugitive CO_2 emissions are the Tier 1 IPCC default emission factors used for underground mining (-50 percent to +100 percent) and surface mining (-67 percent to +200 percent) (IPCC 2019). Additional sources of uncertainty for fugitive CO_2 emission estimates include EIA's annual coal production data and data used for gas recovery projects, such as GHGRP data, state gas sales data, and VAM estimates for the single mine that operates an active VAM project. Uncertainty ranges for these additional data sources are already available, as these are the same data sources used for CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-38. Coal mining CH_4 emissions in 2022 were estimated to be between 34.8 and 47.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20.3 percent below to 9.5 percent above the 2022 emission estimate of 43.6 MMT CO_2 Eq. Coal mining fugitive CO_2 emissions in 2022 were estimated to be between 0.8 and 4.3 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 68.5 percent below to 75.4 percent above the 2022 emission estimate of 2.5 MMT CO_2 Eq.

Table 3-38: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Coal Mining (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH_4	43.6	34.8	47.8	-20%	+9%
Coal Mining	CO_2	2.5	0.8	4.3	-69%	+75%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for coal mining, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating fugitive emissions from

coal mining. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Emission estimates for coal mining rely in large part on data reported by coal mines to EPA's GHGRP. EPA verifies annual facility-level reports through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. All reports submitted to EPA are evaluated by electronic validation and verification checks. If potential errors are identified, EPA will notify the reporter, who can resolve the issue either by providing an acceptable response describing why the flagged issue is not an error or by correcting the flagged issue and resubmitting their annual report. Additional QA/QC and verification procedures occur for each GHGRP subpart. No QA/QC issues or errors were identified in the 2022 Subpart FF data.

Recalculations Discussion

Time series recalculations were performed due to revised historical data from state natural gas sales databases for five mines, which are used to estimate avoided CH_4 emissions. Additionally, calculation errors were identified and corrected for CH_4 emissions avoided from two mines. As a result of recalculations, CH_4 emissions decreased by an average of 0.03 percent across the time series, compared to the previous *Inventory*. The biggest increase in CH_4 emissions was in 1991 where emissions increased by 0.14 percent, compared to the previous *Inventory*. The biggest decrease in CH_4 emissions was in 2006 (0.6 percent). As a result of recalculations, there was a very minor decrease in CH_4 emissions in 2021 (less than 0.005 percent), compared to the previous *Inventory*.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CH_4 and CO_2 emissions from underground and surface mining and CH_4 emissions from post-mining.

3.5 Abandoned Underground Coal Mines (CRT Source Category 1B1a)

Underground coal mines contribute the largest share of coal mine methane (CMM) emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures. As work stops within the mines, CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Annual gross abandoned mine CH_4 emissions ranged from 8.1 to 12.1 MMT CO_2 Eq. from 1990 to 2022, varying, in general, by less than 1 percent to approximately 19 percent from year to year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Gross abandoned mine emissions peaked in 1996 (12.1 MMT CO_2 Eq.) due to the large number of gassy mine[68] closures from 1994 to 1996 (72 gassy mines closed during the three-year period). In spite of this rapid rise, abandoned mine emissions have been generally on the decline since 1996. Since 2002, there have been fewer than twelve gassy mine closures each year. In 2022 there was one gassy mine closure. Gross abandoned mine emissions decreased slightly from 9.2 MMT CO_2 Eq. (330 kt CH_4) in 2021 to 9.1 (324 kt CH_4) MMT CO_2 Eq. in 2022 (see Table 3-39 and Table 3-40). Gross emissions are reduced by CH_4 recovered and used at 51 mines, resulting in net emissions in 2022 of 6.3 MMT CO_2 Eq. (225 kt CH_4).

Table 3-39: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Underground Mines	8.1	9.3	9.9	9.6	9.4	9.2	9.1
Recovered & Used	NO	(2.0)	(3.0)	(2.9)	(2.9)	(3.0)	(2.8)
Total	**8.1**	**7.4**	**6.9**	**6.6**	**6.5**	**6.3**	**6.3**

NO (Not Occurring)
Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-40: CH_4 Emissions from Abandoned Coal Mines (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Underground Mines	288	334	355	341	335	330	324
Recovered & Used	NO	(70)	(107)	(104)	(103)	(106)	(100)
Total	**288**	**264**	**247**	**237**	**232**	**224**	**225**

NO (Not Occurring)
Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate of coal mining, and the flow capacity of the mine in much the same way as the initial rate of a water-free conventional gas well reflects the gas content of the producing formation and the flow capacity of the well. A well or a mine that produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted. Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modeled by mathematical equations and mapped as a type curve. Type curves, which are referred to as decline curves, have been developed for abandoned coal mines. Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline curve used in forecasting production from natural gas wells.

There are sufficient mine level data available to establish decline curves for individual gassy mines abandoned since 1972. For mines abandoned prior to 1972, county level data are available. Mine status information (i.e., whether a mine is sealed, venting, or flooded) is not available for all the abandoned gassy mines. Therefore, a hybrid Tier 2/Tier 3 method was developed to model abandoned gassy mine emissions using Monte Carlo simulations. Tier 3 calculations are used for mines with known status information where decline curves can be used to directly estimate abandoned mine emissions. For mines with unknown status, a Tier 2 approach that estimates basin level emissions is used. This Tier 2 approach relies on data from other mines with known status

[68] A mine is considered a "gassy" mine if it emits more than 100 thousand cubic feet of CH_4 per day (100 Mcfd).

and located within the same basin as the unknown status mines. This approach is consistent with the IPCC 2006 Guidelines as underground mines can be considered point sources and measurement methods are available.

To estimate CH_4 emissions over time for a given abandoned mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption that they will generally have the same initial pressures, permeability, and isotherm. As CH_4 leaves the system, the reservoir pressure (Pr) declines as described by the isotherm's characteristics. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure for a vented mine, and the productivity index (PI), which is expressed as the flow rate per unit of pressure change, is essentially constant at the pressures of interest (atmospheric to 30 psia). The CH_4 flow rate is determined by the laws of gas flow through porous media, such as Darcy's Law. A rate-time equation can be generated that can be used to predict future emissions. This decline through time is hyperbolic in nature and can be empirically expressed as:

Equation 3-3: Decline Function to Estimate Venting Abandoned Mine Methane Emissions

$$q = q_i \left(1 + bD_i t\right)^{\left(-\frac{1}{b}\right)}$$

where,

q = Gas flow rate at time t in million cubic feet per day (mmcfd)

q_i = Initial gas flow rate at time zero (t_o), mmcfd

b = The hyperbolic exponent, dimensionless

D_i = Initial decline rate, 1/year

t = Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability, and adsorption isotherms (EPA 2004).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emissions after mining activities cease, such as sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within eight years and therefore will no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooded mines was established by fitting a decline curve to emissions from field measurements. An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five basins. Using a least squares, curve-fitting algorithm, emissions data were matched to the exponential equation shown below. For this analysis of flooded abandoned mines, there was not enough data to establish basin-specific equations, as was done with the vented, non-flooding mines (EPA 2004). This decline through time can be empirically expressed as:

Equation 3-4: Decline Function to Estimate Flooded Abandoned Mine Methane Emissions

$$q = q_i e^{(-Dt)}$$

where,

q = Gas flow rate at time t in mmcfd

q_i = Initial gas flow rate at time zero (t_o), mmcfd

D = Decline rate, 1/year

t = Elapsed time from t_o (years)

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the flow rate that would exist if the mine had an open vent. The total volume emitted will be the same, but emissions will occur over a longer period of time. The methodology, therefore, treats the emissions prediction from a sealed mine similarly to the emissions prediction from a vented mine, but uses a lower initial rate depending on the degree of sealing. A

computational fluid dynamics simulator was used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × (1 – [initial emissions from sealed mine / emission rate at abandonment prior to sealing]). Significant differences are seen between 50 percent, 80 percent, and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2004).

For active coal mines, those mines producing over 100 thousand cubic feet per day (Mcfd) of CH_4 account for about 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that the 531 abandoned mines closed since 1972 produced CH_4 emissions greater than 100 Mcfd when active. Further, the status of 307 of the 531 mines (or 58 percent) is known to be either: 1) vented to the atmosphere; 2) sealed to some degree (either earthen or concrete seals); or 3) flooded (enough to inhibit CH_4 flow to the atmosphere). The remaining 42 percent of the mines whose status is unknown were placed in one of these three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2004). Table 3-41 presents the count of mines by post-abandonment state, based on EPA's probability distribution analysis.

Table 3-41: Number of Gassy Abandoned Mines Present in U.S. Basins in 2022, Grouped by Class According to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	43	25	50	118	144	262
Illinois	35	3	14	52	31	83
Northern Appl.	49	23	15	87	39	126
Warrior Basin	0	0	16	16	0	16
Western Basins	28	4	2	34	10	44
Total	**155**	**55**	**97**	**307**	**224**	**531**

Note: Totals may not sum due to independent rounding.

Inputs to the decline equation require the average CH_4 emission rate prior to abandonment and the date of abandonment. Generally, these data are available for mines abandoned after 1971; however, such data are largely unknown for mines closed before 1972. Information that is readily available, such as coal production by state and county, is helpful but does not provide enough data to directly employ the methodology used to calculate emissions from mines abandoned before 1972. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1971 mines; thus, their emissions may be characterized by the same decline curves.

During the 1970s, 78 percent of CH_4 emissions from coal mining came from seventeen counties in seven states. Mine closure dates were obtained for two states, Colorado and Illinois, for the hundred-year period extending from 1900 through 1999. The data were used to establish a frequency of mine closure histogram (by decade) and applied to the other five states with gassy mine closures. As a result, basin-specific decline curve equations were applied to the 145 gassy coal mines estimated to have closed between 1920 and 1971 in the United States, representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH_4 emission rates during the 1970s (EPA 2004).

Abandoned mine emission estimates are based on all closed mines known to have active mine CH_4 ventilation emission rates greater than 100 Mcfd at the time of abandonment. For example, for 1990 the analysis included 145 mines closed before 1972 and 258 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database (MSHA 2023). Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect only ventilation emissions for pre-1990 closures. Methane degasification amounts were added to the quantity of CH_4 vented to determine the total CH_4 liberation rate for all mines that closed between 1992 and 2022. Since the sample of gassy mines described above is assumed to account for 78 percent of the pre-1972 and 98 percent of the post-1971 abandoned mine emissions, the modeled results were multiplied by 1.22 and 1.02, respectively, to account for all U.S. abandoned mine emissions.

From 1993 through 2022, emission totals were downwardly adjusted to reflect CH_4 emissions avoided from abandoned mines with CH_4 recovery and use or destruction systems. Currently, there are 51 abandoned mines with recovery projects, including 11 projects at mines abandoned before 1972 (pre-1972 mines) (EPA 2004, CMOP 2022). Because CH_4 recovered by these projects is expected to decline with the age of the mine, CH_4 recovery is assumed to be the total estimated CH_4 liberated based on the mine's decline function except for three recovery projects where additional data are available (COGIS 2018, MSHA 2023).[69]

The *Inventory* totals were not adjusted for abandoned mine CH_4 emissions avoided from 1990 through 1992 due to unavailability of data. Avoided CH_4 emissions from pre-1972 abandoned mines are estimated by multiplying the total estimated emissions from these mines in each decade by the fraction of mines with recovery projects in that decade. For recovery projects at pre-1972 abandoned mines, four projects are at mines abandoned in the 1920s, three in the 1930s, two in the 1950s, and two in the 1960s (EPA 2004).

Reviewing Coalbed Methane Outreach Program data (CMOP 2023) revealed four additional recovery projects starting in 2021. In addition to reviewing CMOP data, the recovery project list was checked against the International Coal Mine Methane Database (GMI 2021). Of the 24 operational recovery projects for U.S. abandoned coal mines currently available in the GMI dataset, 18 are already included in the AMM model. The remaining six projects in the GMI dataset are for mines that are not yet abandoned according to MSHA records (MSHA 2023). Therefore, no new recovery projects were added from the GMI database for the 1990 through 2022 *Inventory*.

Uncertainty

A quantitative uncertainty analysis was conducted for the abandoned coal mine source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. The uncertainty analysis provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the *Inventory* estimate. The results provide the range within which, with 95 percent certainty, emissions from this source category are likely to fall.

As discussed above, the parameters for which values must be estimated for each mine to predict its decline curve are: 1) the coal's adsorption isotherm; 2) CH_4 flow capacity as expressed by permeability; and 3) pressure at abandonment. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each parameter. The range of values is not meant to capture the extreme values, but rather values that represent the highest and lowest quartile of the cumulative probability density function of each parameter. Once the low, mid, and high values are selected, they are applied to a probability density function.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-42. Annual abandoned coal mine CH_4 emissions in 2022 were estimated to be between 5.0 and 7.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 21 percent below to 20 percent above the 2022 emission estimate of 6.3 MMT CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is available for use in the methodology for mines closed in 1972 and later years. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH_4 liberation rates at the time of abandonment exist.

[69] Data from a state oil and gas database (COGIS) is used for one project and the mine status information from MSHA for two mines (sealed and flooded) indicate zero recovery emissions for these projects.

Table 3-42: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	6.3	5.0	7.5	-21%	+20%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for abandoned coal mines, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating emissions from abandoned coal mines. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Recalculations Discussion

Four new abandoned mine methane recovery projects were added to the AMM model during the current *Inventory* (CMOP 2023). CMOP data indicate these recovery projects were started in 2021. Time series recalculations were performed for 2021. As a result of recalculations, CH_4 emissions decreased by 2 percent in 2021, compared to the previous *Inventory*.

3.6 Petroleum Systems (CRT Source Category 1B2a)

This category (1B2a) is defined in the IPCC methodological guidance as fugitive emissions from petroleum systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil exploration, production, transportation, and refining operations. During these activities, CH_4 is released to the atmosphere as emissions from leaks, venting (including emissions from operational upsets), and flaring. Carbon dioxide emissions from petroleum systems are primarily associated with onshore and offshore crude oil production and refining operations. Note, CO_2 emissions in petroleum systems exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in the fossil fuel combustion chapter (see Section 3.1). Emissions of N_2O from petroleum systems are primarily associated with flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from petroleum systems in 2022 were 61.6 MMT CO_2 Eq., an increase of 4 percent from 1990, primarily due to increases in CO_2 emissions. Total emissions decreased by 6 percent from 2010 levels and have decreased by 15 percent since 2021. Total CO_2 emissions from petroleum systems in 2022 were 21.97 MMT CO_2 (21,967 kt CO_2), 2.3 times higher than in 1990. Total CO_2 emissions in 2022 were 1.6 times higher than in 2010 and 9 percent lower than in 2021. Total CH_4 emissions from petroleum systems in 2022 were 39.6 MMT CO_2 Eq. (1,415 kt CH_4), a decrease of 20 percent from 1990. Since 2010, total CH_4 emissions decreased by 24 percent; and since 2021, CH_4 emissions decreased by 19 percent. Total N_2O emissions from petroleum systems in 2022 were 0.048 MMT CO_2 Eq. (0.179 kt N_2O), 3.8 times higher than in 1990, 2.8 times higher than in 2010, and 142 percent higher than in 2021. Since 1990, U.S. oil production has increased by 56 percent. In 2022, U.S. oil production was 163 percent higher than in 2010 and 7 percent higher than in 2021.

Each year, some estimates in the *Inventory* are recalculated with improved methods and/or data. These improvements are implemented consistently across the entire *Inventory's* time series (i.e., 1990 to 2022) to ensure that the trend is representative of changes in emissions levels. Recalculations in petroleum systems in this year's *Inventory* include:

- Updates to oil and gas production volumes, produced water production volumes, and well counts using the most recent data from Enverus.
- Updates to oil and gas production volumes using the most recent data from the United States Energy Information Administration (EIA)
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions
- Recalculations due to methodological updates to completions and workovers.

The Recalculations Discussion section below provides more details on the updated methods.

Exploration. Exploration includes well drilling, testing, and completions. Exploration accounts for less than 0.5 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The predominant sources of CH_4 emissions from exploration are hydraulically fractured oil well completions. Other sources include well testing, well drilling, and well completions without hydraulic fracturing. Since 1990, exploration CH_4 emissions have decreased 96 percent, and while the number of hydraulically fractured wells completed increased 64 percent, there were decreases in the fraction of such completions without reduced emissions completions (RECs) or flaring. Emissions of CH_4 from exploration were highest in 2008, over 70 times higher than in 2022; and lowest in 2022. Emissions of CH_4 from exploration decreased 39 percent from 2021 to 2022, due to a decrease in emissions from hydraulically fractured oil well completions with RECs. Exploration accounts for 1 percent of total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. Emissions of CO_2 from exploration in 2022 were 25 percent lower than in 1990, and decreased by 50 percent from 2021, largely due to a decrease in emissions from hydraulically fractured oil well completions with REC and flaring (by 58 percent from 2021). Emissions of CO_2 from exploration were highest in 2014, over 13 times higher than in 2022. Exploration accounts for less than 0.5 percent of total N_2O emissions from petroleum systems in 2022. Emissions of N_2O from exploration in 2022 are 29 percent lower than in 1990, and 56 percent lower than in 2021, due to hydraulically fractured oil well completions with flaring.

Production. Production accounts for 97 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The predominant sources of emissions from production field operations are pneumatic controllers, offshore oil platforms, equipment leaks, produced water, gas engines, chemical injection pumps, and associated gas flaring. In 2022, these seven sources together accounted for 93 percent of the CH_4 emissions from production. Since 1990, CH_4 emissions from production have decreased by 15 percent primarily due to decreases in emissions from offshore production. Overall, production segment CH_4 emissions decreased by 19 percent from 2021 levels due primarily to lower pneumatic controller emissions. Production emissions account for 86 percent of the total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2022. The principal sources of CO_2 emissions are associated gas flaring, miscellaneous production flaring, and oil tanks with flares. In 2022, these three sources together accounted for 96 percent of the CO_2 emissions from production. In 2022, CO_2 emissions from production were 3.1 times higher than in 1990, due to increases in flaring emissions from associated gas flaring, miscellaneous production flaring, and tanks. Overall, in 2022, production segment CO_2 emissions decreased by 8 percent from 2021 levels primarily due to decreases in associated gas flaring in the Williston Basin and oil tanks with flares. Production emissions accounted for 84 percent of the total N_2O emissions from petroleum systems in 2022. The principal sources of N_2O emissions are oil tanks with flares and associated gas flaring, accounting for 90% of N_2O emissions from the production segment in 2022. In 2022, N_2O emissions from production were 8.0 times higher than in 1990 and were 3.5 times higher than in 2021.

Crude Oil Transportation. Emissions from crude oil transportation account for a very small percentage of the total emissions (including leaks, vents, and flaring) from petroleum systems. Crude oil transportation activities account for 0.6 percent of total CH_4 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations accounted for 81 percent of CH_4 emissions from crude oil transportation in 2022. Since 1990,

CH_4 emissions from transportation have increased by 27 percent. In 2022, CH_4 emissions from transportation increased by 6 percent from 2021 levels. Crude oil transportation activities account for less than 0.01 percent of total CO_2 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations account for 81 percent of CO_2 emissions from crude oil transportation.

Crude Oil Refining. Crude oil refining processes and systems account for 2 percent of total fugitive (including leaks, vents, and flaring) CH_4 emissions from petroleum systems in 2022. This low share is because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is a negligible amount of CH_4 in all refined products. Within refineries, flaring accounts for 42 percent of the CH_4 emissions, while delayed cokers, uncontrolled blowdowns, and equipment leaks account for 19, 14 and 11 percent, respectively. Fugitive CH_4 emissions from refining of crude oil have decreased by 4 percent since 1990, and decreased by 3 percent from 2021; however, like the transportation subcategory, this increase has had little effect on the overall emissions of CH_4 from petroleum systems. Crude oil refining processes and systems account for 13 percent of total fugitive (including leaks, vents, and flaring) CO_2 emissions from petroleum systems. Of the total fugitive CO_2 emissions from refining, almost all (about 99 percent) of it comes from flaring.[70] Since 1990, refinery fugitive CO_2 emissions decreased by 10 percent and have decreased by 5 percent from 2021 levels, due to a decrease in flaring. Flaring occurring at crude oil refining processes and systems accounts for 16 percent of total fugitive N_2O emissions from petroleum systems. In 2022, refinery fugitive N_2O emissions increased by 4 percent since 1990 and decreased by 5 percent from 2021 levels.

Table 3-43: Total Greenhouse Gas Emissions (CO_2, CH_4, and N_2O) from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	3.4	5.7	3.2	2.5	1.1	0.8	0.4
Production	51.6	48.1	86.7	90.6	77.3	68.0	57.4
Transportation	0.2	0.1	0.2	0.3	0.2	0.2	0.2
Crude Refining	3.9	4.4	3.7	4.4	3.6	3.7	3.6
Total	**59.0**	**58.5**	**93.8**	**97.8**	**82.3**	**72.8**	**61.6**

Note: Totals may not sum due to independent rounding.

Table 3-44: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	**3.0**	**5.3**	**0.5**	**0.5**	**0.3**	**0.2**	**0.1**
Production	**45.5**	**42.0**	**57.5**	**50.6**	**52.0**	**47.5**	**38.6**
Pneumatic Controllers	21.3	22.7	34.7	24.7	31.3	28.1	19.4
Offshore Production	9.9	7.2	5.5	5.4	5.1	5.1	5.1
Equipment Leaks	2.3	2.8	3.7	3.9	3.2	3.2	3.1
Gas Engines	2.3	2.0	2.5	2.6	2.5	2.4	2.5
Produced Water	2.6	1.8	2.7	2.8	2.5	2.6	2.7
Chemical Injection Pumps	1.3	2.2	3.0	3.4	2.7	2.4	2.2
Assoc Gas Flaring	0.6	0.4	1.9	2.5	1.3	1.0	0.8
Other Sources	5.3	2.8	3.5	5.3	3.3	2.7	2.7
Crude Oil Transportation	**0.2**	**0.1**	**0.2**	**0.3**	**0.2**	**0.2**	**0.2**
Refining	**0.7**	**0.8**	**0.8**	**0.9**	**0.7**	**0.7**	**0.7**
Total	**49.4**	**48.2**	**59.0**	**52.2**	**53.3**	**48.6**	**39.6**

Note: Totals may not sum due to independent rounding.

[70] Petroleum Systems includes fugitive emissions (leaks, venting, and flaring). In many industries, including petroleum refineries, the largest source of onsite CO_2 emissions is often fossil fuel combustion, which is covered in Section 3.1 of this chapter.

Table 3-45: CH_4 Emissions from Petroleum Systems (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	**106**	**189**	**19**	**16**	**12**	**7**	**4**
Production	**1,626**	**1,500**	**2,052**	**1,809**	**1,858**	**1,696**	**1,377**
Pneumatic Controllers	761	811	1,240	881	1,119	1,003	694
Offshore Production	353	259	197	193	183	182	182
Equipment Leaks	82	101	132	138	115	114	112
Gas Engines	81	70	91	93	89	87	88
Produced Water	92	64	95	99	90	92	95
Chemical Injection Pumps	47	80	108	123	96	85	80
Assoc Gas Flaring	20	14	66	91	47	35	30
Other Sources	189	100	124	190	119	97	98
Crude Oil Transportation	**7**	**5**	**8**	**9**	**8**	**8**	**8**
Refining	**26**	**29**	**28**	**31**	**26**	**25**	**25**
Total	**1,765**	**1,723**	**2,108**	**1,865**	**1,904**	**1,737**	**1,415**

Note: Totals may not sum due to independent rounding.

Table 3-46: CO_2 Emissions from Petroleum Systems (MMT CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	0.4	0.5	2.7	2.0	0.8	0.6	0.3
Production	6.0	6.1	29.2	39.9	25.2	20.5	18.8
Transportation	+	+	+	+	+	+	+
Crude Refining	3.2	3.6	2.9	3.6	2.9	3.0	2.9
Total	**9.6**	**10.2**	**34.8**	**45.5**	**28.9**	**24.1**	**22.0**

+ Does not exceed 0.05 MMT CO_2.

Note: Totals may not sum due to independent rounding.

Table 3-47: CO_2 Emissions from Petroleum Systems (kt CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	398	465	2,684	2,044	798	601	300
Production	6,012	6,143	29,215	39,882	25,244	20,516	18,793
Transportation	0.9	0.7	1.2	1.3	1.2	1.1	1.2
Crude Refining	3,174	3,602	2,877	3,571	2,893	3,021	2,872
Total	**9,585**	**10,210**	**34,777**	**45,498**	**28,937**	**24,140**	**21,967**

Table 3-48: N_2O Emissions from Petroleum Systems (Metric Tons CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	180	209	1,161	820	353	290	127
Production	4,996	4,588	30,822	28,047	13,614	11,414	39,859
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	7,262	8,243	7,405	9,312	7,575	7,920	7,523
Total	**12,438**	**13,040**	**39,387**	**38,180**	**21,542**	**19,624**	**47,510**

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-49: N_2O Emissions from Petroleum Systems (Metric Tons N_2O)

Activity	1990	2005	2018	2019	2020	2021	2022
Exploration	0.7	0.8	4.4	3.1	1.3	1.1	0.5
Production	18.9	17.3	116.3	105.8	51.4	43.1	150.4
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	27.4	31.1	27.9	35.1	28.6	29.9	28.4
Total	**46.9**	**49.2**	**148.6**	**144.1**	**81.3**	**74.1**	**179.3**

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.5 for the full time series of emissions data, activity data, emission factors, and additional information on methods and data sources.

Petroleum systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil exploration, production field operations, crude oil transportation activities, and refining operations. Generally, emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity). Certain sources within petroleum refineries are developed using an IPCC Tier 3 approach (i.e., all refineries in the nation report facility-level emissions data to the GHGRP, which are included directly in the national emissions estimates here). Other estimates are developed with a Tier 2 approach. Tier 1 approaches are not used.

EPA did not receive stakeholder feedback on updates in the *Inventory* through EPA's stakeholder process on oil and gas in the *Inventory*. More information on the stakeholder process can be found online.[71]

Emission Factors. Key references for emission factors include *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (GRI/EPA 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997), *Global Emissions of Methane from Petroleum Sources* (API 1992), consensus of industry peer review panels, Bureau of Ocean Energy Management (BOEM) reports, *Nonpoint Oil and Gas Emission Estimation Tool* (EPA 2017), and analysis of GHGRP data (EPA 2023).

Emission factors for hydraulically fractured (HF) oil well completions and workovers (in four control categories) were developed at the basin level using EPA's GHGRP data; year-specific data were used to calculate basin-specific emission factors from 2016-forward and the year 2016 emission factors were applied to all prior years in the time series. For basins not reporting to the GHGRP, Subpart W average emission factors were used. For more information, please see the 2023 memoranda available online.[72]

The emission factors for well testing and associated gas venting and flaring were developed using year-specific GHGRP data for years 2015 forward; earlier years in the time series use 2015 emission factors. For miscellaneous production flaring, year-specific emission factors were developed for years 2015 forward from GHGRP data, an emission factor of 0 (assumption of no flaring) was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. For more information, please see memoranda available online.[73] For offshore oil production, emission factors were calculated using BOEM data for offshore facilities in federal waters of the Gulf of Mexico (and these data were also applied to facilities located in state waters of the Gulf of Mexico) and GHGRP data for offshore facilities off the coasts of California and Alaska. For

[71] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[72] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[73] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

many other sources, emission factors were held constant for the period 1990 through 2022, and trends in emissions reflect changes in activity levels. Emission factors from EPA 1999 are used for all other production and transportation activities.

For associated gas venting and flaring and miscellaneous production flaring, emission factors were developed on a production basis (i.e., emissions per unit oil produced). Additionally, for these two sources, basin-specific activity and emission factors were developed for each basin that in any year from 2011 forward contributed at least 10 percent of total source emissions (on a CO_2 Eq. basis) in the GHGRP. For associated gas venting and flaring, basin-specific factors were developed for four basins: Williston, Permian, Gulf Coast, and Anadarko. For miscellaneous production flaring, basin-specific factors were developed for three basins: Williston, Permian, and Gulf Coast. For each source, data from all other basins were combined, and activity and emission factors were developed for the other basins as a single group.

For pneumatic controllers and tanks, basin-specific emission factors were calculated for all the basins reporting to the GHGRP. These emission factors were calculated for all the years with applicable GHGRP data (i.e., 2011 - 2022 or 2015 - 2022). For the remaining basins (i.e., basins not reporting to the GHGRP), Subpart W average emission factors were used. For more information, please see memoranda available online.[3]

For the exploration and production segments, in general, CO_2 emissions for each source were estimated with GHGRP data or by multiplying CO_2 content factors by the corresponding CH_4 data, as the CO_2 content of gas relates to its CH_4 content. Sources with CO_2 emission estimates calculated using GHGRP data include HF completions and workovers, associated gas venting and flaring, tanks, well testing, pneumatic controllers, chemical injection pumps, miscellaneous production flaring, and certain offshore production facilities (those located off the coasts of California and Alaska). For these sources, CO_2 was calculated using the same methods as used for CH_4. Carbon dioxide emission factors for offshore oil production in the Gulf of Mexico were derived using data from BOEM, following the same methods as used for CH_4 estimates. For other sources, the production field operations emission factors for CO_2 are generally estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in produced associated gas.

For the exploration and production segments, N_2O emissions were estimated for flaring sources using GHGRP or BOEM OGOR-B data and the same method used for CO_2. Sources with N_2O emissions in the exploration segment include well testing and HF completions with flaring. Sources with N_2O emissions in the production segment include associated gas flaring, tank flaring, miscellaneous production flaring, HF workovers with flaring, and flaring from offshore production sources.

For crude oil transportation, emission factors for CH_4 were largely developed using data from EPA (1997), API (1992), and EPA (1999). Emission factors for CO_2 were estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in whole crude post-separator.

For petroleum refining activities, year-specific emissions from 2010 forward were directly obtained from EPA's GHGRP. All U.S. refineries have been required to report CH_4, CO_2, and N_2O emissions for all major activities starting with emissions that occurred in 2010. The reported total CH_4, CO_2, and N_2O emissions for each activity was used for the emissions in each year from 2010 forward. To estimate emissions for 1990 to 2009, the 2010 to 2013 emissions data from GHGRP along with the refinery feed data for 2010 to 2013 were used to derive CH_4 and CO_2 emission factors (i.e., sum of activity emissions/sum of refinery feed) and 2010 to 2017 data were used to derive N_2O emission factors; these emission factors were then applied to the annual refinery feed in years 1990 to 2009. GHGRP delayed coker CH_4 emissions for 2010 through 2017 were increased using the ratio of certain reported emissions for 2018 to 2017, to account for a more accurate GHGRP calculation methodology that was implemented starting in reporting year 2018.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5.

Activity Data. References for activity data include Enverus data (Enverus 2023), Energy Information Administration (EIA) reports, *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (EPA/GRI 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), consensus of industry peer review panels, BOEM reports, the Oil & Gas Journal, the Interstate Oil and Gas Compact Commission, the United States Army Corps of Engineers, and analysis of GHGRP data (EPA 2023).

For HF oil well completions and workovers, pneumatic controllers, equipment leaks, chemical injection pumps, and tanks, basin-specific activity factors were calculated for all the basins reporting to the GHGRP. These factors were calculated for all the years with applicable GHGRP data (i.e., 2011 through 2022, 2016 through 2022, or 2015 through 2022). For the remaining basins (i.e., basins not reporting to the GHGRP), GHGRP average activity factors were used. For more information, please see memoranda available online.[74]

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed to estimate values, consistent with IPCC good practice. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA/GRI (1996) and/or GHGRP data. In some cases, activity data are developed by interpolating between recent data points (such as from GHGRP) and earlier data points, such as from EPA/GRI (1996). Lastly, in limited instances the previous year's data were used if current year data were not yet available.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5. The United States reports data to the UNFCCC using this *Inventory* report along with Common Reporting Tables (CRTs). This note is provided for those reviewing the CRTs: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRT 1.B.2. Disaggregating flaring and venting estimates across the Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

As noted above, EPA's GHGRP data, available starting in 2010 for refineries and in 2011 for other sources, have improved estimates of emissions from petroleum systems. Many of the previously available datasets were collected in the 1990s. To develop a consistent time series for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2009 or 2014 by interpolating activity data or emission factors or both between 1992 (when GRI/EPA data are available) and 2010 or 2015 data points. Information on time-series consistency for sources updated in this year's *Inventory* can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For information on other sources, please see the Methodology and Time-Series Consistency discussion above and Annex 3.5.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize uncertainty for petroleum systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 uncertainty memo)* and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates (2021 uncertainty memo)*.[75]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from petroleum systems for the current *Inventory*. For the CH_4 uncertainty analysis, EPA focused on the eight highest methane-emitting sources for the year 2022, which together emitted 75 percent of methane from petroleum systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. For the CO_2 uncertainty analysis, EPA focused on the five highest-emitting sources for the year 2022 which together emitted 81 percent of CO_2 from petroleum systems in 2022, and extrapolated the estimated uncertainty for the remaining

[74] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[75] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

sources. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. For emission factors that are derived from methane emissions measurement studies, the PDFs are commonly determined to be lognormally distributed (GRI/EPA 1996; EPA 1999). For activity data that are derived from national datasets, the PDFs are set to a uniform distribution (see 2018 and 2021 uncertainty memos). Many emission factors and activity factors are calculated using subpart W data, and for these, the @RISK add-in determines the best fitting PDF (e.g., lognormal, gaussian), based on bootstrapping of the underlying data (see 2018 and 2021 uncertainty memos). The IPCC guidance notes that in using this Approach 2 method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future *Inventories*.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2022, using the recommended IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-50. Petroleum systems CH_4 emissions in 2022 were estimated to be between 32.7 and 48.6 MMT CO_2 Eq., while CO_2 emissions were estimated to be between 17.9 and 27.4 MMT CO_2 Eq. at a 95 percent confidence level. Petroleum systems N_2O emissions in 2022 were estimated to be between 0.039 and 0.059 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, associated gas venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., reduced emissions completions were not used early in the time series).

Table 3-50: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petroleum Systems	CH_4	39.6	32.7	48.6	-18%	+23%
Petroleum Systems	CO_2	22.0	17.9	27.4	-19%	+25%
Petroleum Systems	N_2O	0.048	0.039	0.059	-19%	+25%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2022 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

QA/QC and Verification Discussion

In order to ensure the quality of the emission estimates for petroleum systems, general (IPCC Tier 1) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8.

The petroleum systems emission estimates in the *Inventory* are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the emission calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the *Inventory* are consistent with current industry practices. EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[76]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current *Inventory*. EPA held a stakeholder webinar on greenhouse gas data for oil and gas in October of 2023. EPA released memos detailing updates under consideration and requesting stakeholder feedback. EPA did not receive stakeholder feedback for the updates under consideration for the current *Inventory*.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the *Inventory*. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes, and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of *Inventory* estimates. In the past few years, EPA has reviewed, and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates.

A key challenge in using these types of studies to assess *Inventory* results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the *Inventory* and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level *Inventory* with measurement results that may be at other spatial and temporal scales, EPA has developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[77] The most recent version of the gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* estimates for the years 2012 through 2018. The gridded inventory improves efforts to compare results of this *Inventory* with atmospheric studies.

As discussed above, refinery emissions are quantified by using the total emissions reported to GHGRP for the refinery emission categories included in petroleum systems. Subpart Y has provisions that refineries are not required to report under Subpart Y if their emissions fall below certain thresholds. Each year, a review is conducted to determine whether an adjustment is needed to the Inventory emissions to include emissions from refineries that stopped reporting to the GHGRP. Based on the review of the most recent GHGRP data, EPA did not identify any additional refineries that would require gap filling. There are a total of 7 refineries that EPA previously identified (i.e., during the 1990 through 2021 *Inventory* and prior versions) as not reporting to the GHGRP and continued to gap fill annual emissions for these refineries. EPA used the last reported emissions (by source) for these refineries as proxy to gap fill annual emissions.

[76] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[77] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting and presented information to stakeholders regarding the updates under consideration. In November 2023, EPA released draft memoranda that discussed changes under consideration and requested stakeholder feedback on those changes. EPA then released final memoranda documenting the methodology implemented in the current Inventory.[78] The memorandum cited in the Recalculations Discussion below is: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Completion and Workover Emissions (*Completions and Workovers* memo).

EPA evaluated relevant information available and made an updates to the *Inventory* for hydraulically fractured (HF) oil well completions and workovers. General information for these source specific recalculations are presented below and details are available in the *Completions and Workovers* memo.

In addition to the updates to the sources mentioned above, for certain sources, CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. The emissions changes were mostly due to GHGRP data submission revisions. These sources are discussed below and include associated gas flaring, miscellaneous production flaring, pneumatic controllers, oil tanks, chemical injection pumps, produced water, offshore production (in Gulf of Mexico federal waters), gas engines, and refinery flaring.

The combined impact of revisions to 2021 petroleum systems CH_4 emission estimates on a CO_2-equivalent basis, compared to the previous *Inventory*, is a decrease from 50.2 to 48.6 MMT CO_2 Eq. (1.5 MMT CO_2 Eq., or 3 percent). The recalculations resulted in lower CH_4 emission estimates on average across the 1990 through 2021 time series, compared to the previous *Inventory*, by 2.5 MMT CO_2 Eq., or 5 percent.

The combined impact of revisions to 2021 petroleum systems CO_2 emission estimates, compared to the previous *Inventory*, is a decrease from 24.7 to 24.1 MMT CO_2 (0.5 MMT CO_2, or 2 percent). The recalculations resulted in lower emission estimates on average across the 1990 through 2021 time series, compared to the previous *Inventory*, by 0.1 MMT CO_2 Eq., or 0.2 percent.

The combined impact of revisions to 2021 petroleum systems N_2O emission estimates on a CO_2-equivalent basis, compared to the previous *Inventory*, is a decrease of 0.002 MMT CO_2, Eq. or 10.2 percent. The recalculations resulted in an average decrease in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 0.001 MMT CO_2 Eq., or 7.4 percent.

In Table 3-51 and Table 3-52 below are categories in petroleum systems with updated methodologies or with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. For more information, please see the discussion below.

Table 3-51: Recalculations of CO_2 in Petroleum Systems (MMT CO_2)

Segment/Source	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.5***	**0.6**	**0.3**
HF Completions	*0.5*	0.6	0.3
Production	***20.0***	**20.5**	**18.8**
Tanks	*5.4*	5.6	4.5
HF Workovers	*0.2*	+	+
Pneumatic Controllers	*0.1*	0.1	0.1
Equipment Leaks	*+*	+	+
Chemical Injection Pumps	*+*	+	+

[78] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2022) *Inventory* are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Miscellaneous Production Flaring	*4.2*	4.6	5.0
Transportation	***+***	**+**	**+**
Refining	***4.2***	**3.0**	**2.9**
Flares	*4.2*	3.0	2.8
Petroleum Systems Total	***24.7***	**24.1**	**22.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-52: Recalculations of CH_4 in Petroleum Systems (MMT CO_2 Eq.)

Segment/Source	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.2***	**0.2**	**0.1**
HF Completions	*0.1*	0.2	0.1
Production	***48.9***	**47.5**	**38.6**
Pneumatic Controllers	*28.4*	28.1	19.4
Chemical Injection Pumps	*3.2*	2.4	2.2
Produced Water	*2.5*	2.6	2.7
Offshore Production from GOM Federal Waters (vented and leaks)	*4.7*	4.4	4.3
HF Workovers	*0.1*	+	+
Gas Engines	*2.5*	2.4	2.5
Associated Gas Flaring	*0.8*	1.0	0.8
Transportation	***0.2***	**0.2**	**0.2**
Refining	***0.8***	**0.7**	**0.7**
Petroleum Systems Total	***50.2***	**48.6**	**39.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Exploration

HF Completions (Methodological Update)

EPA updated the calculation methodology for HF completions to use basin-level HF completion counts from Enverus and basin-specific activity factors and emission factors calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national annual average activity and emission factors calculated using Subpart W data were applied to national activity data counts to estimate HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 (first year of GHGRP data for this source) through RY2022. For basin-level HF completion event counts, EPA used Enverus data for 1990 to 2010 and Subpart W for 2011 forward. For the fraction of completions in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well completions were non-REC for 1990 to 2000. The previous *Inventory* also assumed that 10 percent of HF completions were non-REC with flaring from 1990 to 2010 (based on national Subpart W data for RY2011 and RY2012); EPA updated this value using basin-specific Subpart W data for RY2011 and RY2012. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data and used linear interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

Comparing the final completion emissions and those presented at the October 2023 webinar and in the November 2023 *Completions and Workovers* memo, the final estimates are higher for certain completion categories. These emissions increases are due not to the basin-level methodology changes discussed here but rather to changes in the Enverus dataset. EPA applied the same data processing steps to Enverus data in the fall of 2023 as it did for the previous Enverus data analysis (conducted in 2021) and data changes led to many more completions being classified as HF completions.

As a result of this methodological update, CH_4 emissions estimates are on average 10 percent lower across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 41 percent higher than in the previous *Inventory*. The largest increase in the CH_4 emissions estimates compared to the previous *Inventory* is 42 percent in 2016, and the largest decrease is 35 percent in 1999. The decrease in CH_4 emissions is predominantly due to HF completions that were non-REC with venting. Basins such as the Permian basin (basin 430), Williston basin (basin 395), and Denver basin (basin 540) had a high number of HF oil well completion events over the time series. However, they had low EFs for non-REC with venting, decreasing the overall CH_4 emissions. The update resulted in CO_2 emissions estimates that are on average 33 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 29 percent higher than in the previous *Inventory*. The largest increase in CO_2 emissions estimates compared to the previous *Inventory* is 80 percent in 2000, and the largest decrease is 17 percent in 2018. The increase in CO_2 emissions is due to HF completions that were non-REC with flaring and REC with flaring. The Permian basin (basin 430) had the highest emissions across the time series for completions that were non-REC with flaring and REC with flaring. The Permian basin had the highest number of HF oil well completions and high EFs for both control categories.

Table 3-53: HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	95,717	179,290	380	1,126	845	244	509
HF Completions – Non-REC with Flaring	898	1,190	2,797	2,801	1,989	1,272	1,269
HF Completions - REC with Venting	NO	NO	5,478	5,466	6,212	1,114	912
HF Completions - REC with Flaring	NO	NO	9,637	6,188	1,945	3,620	685
Total Emissions	**96,615**	**180,480**	**18,292**	**15,581**	**10,992**	**6,250**	**3,375**
Previous Estimate	*143,304*	*202,773*	*18,090*	*14,864*	*10,568*	*4,430*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-54: HF Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	3	4	+	+	+	+	+
HF Completions – Non-REC with Flaring	155	240	485	762	355	262	131
HF Completions - REC with Venting	NO	NO	+	+	+	+	+
HF Completions - REC with Flaring	NO	NO	2,165	1,278	441	338	141
Total Emissions	**157**	**244**	**2,651**	**2,041**	**797**	**601**	**272**
Previous Estimate	*119*	*168*	*3,174*	*2,431*	*836*	*466*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Production

HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national HF workover counts calculated using analyses for NSPS OOOO (i.e., 1 percent of HF oil wells were worked over annually) and national annual average emission factors calculated using Subpart W data were applied to estimate HF oil well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors (AFs) and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, instead of applying a 1 percent workover rate to HF oil wells, EPA developed year- and basin-specific Subpart W AFs for 2016 (the first year of GHGRP data for this source) forward that represent the number of HF workovers per oil well. Year 2016 Subpart W AFs were applied to all prior years for each basin. For the fraction of workovers in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF oil well workovers were non-REC for 1990 to 2007 and 10 percent flaring from 1990 to 2007. For 2016 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data at the basin level and used linear interpolation between 2008 and 2015 to determine the percent of oil wells with RECs and the percent flaring. EPA developed year- and basin-specific Subpart W EFs for 2016 forward. Year 2016 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates are on average 62 percent lower across the time series than in the previous *Inventory*. The largest decrease in CH_4 emissions estimates compared to the previous *Inventory* is 97 percent in 2021 and the smallest decrease is 39 percent in 2018. The 2021 CH_4 emissions estimate is 97 percent lower than in the previous *Inventory*. The update resulted in CO_2 emissions estimates that are on average 51 percent lower than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 97 percent lower than in the previous *Inventory*. The largest decrease in CO_2 emissions estimates compared to the previous *Inventory* is 97 percent in 2021 and the smallest decrease is 26 percent in 1990. The decrease in emissions for both CH_4 and CO_2 was primarily due to the change in calculation method for workover counts. HF oil well workover counts decreased by an average of 52 percent across the 1990 to 2021 time series compared to the previous *Inventory*.

Table 3-55: HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	17,639	16,244	87	1,339	5	16	35
HF Workovers – Non-REC with Flaring	104	96	11	7	11	20	NO
HF Workovers - REC with Venting	NO	NO	1,304	331	130	5	63
HF Workovers - REC with Flaring	NO	NO	222	75	14	19	33
Total Emissions	**17,744**	**16,340**	**1,623**	**1,753**	**160**	**60**	**130**
Previous Estimate	*37,696*	*41,993*	*2,670*	*3,679*	*3,873*	*2,151*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-56: HF Workovers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	431	408	5	63	+	1	6
HF Workovers – Non-REC with Flaring	22,654	21,076	2,544	2,093	1,947	2,532	NO

HF Workovers - REC with Venting	NO	NO	17	14	4	+	3
HF Workovers - REC with Flaring	NO	NO	51,135	18,285	5,987	2,768	6,095
Total Emissions	**23,085**	**21,484**	**53,701**	**20,456**	**7,939**	**5,301**	**6,105**
Previous Estimate	*31,219*	*34,778*	*89,049*	*97,515*	*97,766*	*205,160*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Pneumatic Controllers (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for pneumatic controllers to use basin-specific activity factors and emission factors by bleed type (i.e., low, high, intermittent bleed) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated pneumatic controller CO_2 emissions using basin-specific emissions data such that the CO_2 emissions reflect the unique CO_2 composition of the gas in a basin.

The update for pneumatic controller CO_2 emission estimates resulted in an average increase of 61 percent across the time series and an increase of 57 percent in 2021, compared to the previous *Inventory*.

In addition, methane emissions for pneumatic controllers were impacted due to recalculations with updated data. Methane emissions from onshore production pneumatic controllers are an average of 2 percent lower across the time series and 1 percent lower in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-57: Pneumatic Controllers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
High Bleed Controllers	94,495	39,873	5,056	5,369	5,778	4,260	2,403
Low Bleed Controllers	7,109	4,132	3,740	4,819	3,704	4,561	3,992
Intermittent Bleed Controllers	NO	26,370	75,579	80,855	82,493	80,063	70,328
Total Emissions	**101,604**	**70,374**	**84,374**	**91,044**	**91,975**	**88,884**	**76,723**
Previous Estimate	*42,406*	*46,477*	*70,322*	*49,460*	*63,104*	*56,641*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Table 3-58: Pneumatic Controllers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
High Bleed Controllers	709,796	481,760	71,824	72,432	86,363	44,611	23,712
Low Bleed Controllers	51,129	62,162	32,106	50,770	36,740	46,060	35,439
Intermittent Bleed Controllers	NO	267,220	1,135,995	758,001	996,250	912,391	634,400
Total Emissions	**760,925**	**811,142**	**1,239,924**	**881,203**	**1,119,352**	**1,003,063**	**693,551**
Previous Estimate	*759,970*	*832,929*	*1,260,259*	*886,382*	*1,130,899*	*1,015,080*	*NA*

NO (Not Occurring)
NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

Equipment Leaks (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for onshore production equipment leaks to use basin-specific equipment-level activity factors (e.g., separators per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated

equipment leak CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emissions factors for onshore production segment equipment leaks. Note, this methodological update applies only for activity factors. The previous *Inventory's* CO_2 emission factors for onshore production segment equipment leaks (by equipment type) were retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates resulted in an average increase of 7 percent across the time series and an increase of 18 percent in 2021, compared to the previous *Inventory*. Years 2015 to 2021 were impacted more by the update, with an average increase of 28 percent compared to the previous *Inventory*.

Table 3-59: Equipment Leaks National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Oil Wellheads (heavy crude)	2	2	2	1	1	1	1
Oil Wellheads (light crude)	3,159	2,857	3,330	3,416	3,280	3,272	3,195
Separators (heavy crude)	1	1	1	1	+	+	+
Separators (light crude)	613	868	2,280	2,114	1,601	1,443	1,411
Heater/Treaters (light crude)	508	474	786	1,028	846	951	905
Headers (heavy crude)	+	+	+	+	+	+	+
Headers (light crude)	185	458	712	843	432	430	485
Total Emissions	**4,468**	**4,660**	**7,111**	**7,403**	**6,161**	**6,098**	**5,997**
Previous Estimate	*4,453*	*4,681*	*5,396*	*5,351*	*5,159*	*5,159*	*NA*

+ Does not exceed 0.05 MT CO_2.
NA (Not Applicable)

Chemical Injection Pumps (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for chemical injection pumps to use basin-specific equipment-level activity factors (e.g., pumps per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated chemical injection pump CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emission factor. Note, this methodological update applies only for activity factors. The previous *Inventory's* chemical injection pumps CO_2 emission factor was retained and used to develop CO_2 estimates. The update for CO_2 emission estimates resulted in an average decrease of 29 percent across the time series and a decrease of 35 percent in 2021, compared to the previous *Inventory*.

Table 3-60: Chemical Injection Pump National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	2,646	4,464	5,955	6,784	5,338	4,749	4,449
Previous Estimate	*4,506*	*6,522*	*7,689*	*7,625*	*7,351*	*7,351*	*NA*

NA (Not Applicable)

Storage Tanks (Recalculation with Updated Data)

Carbon dioxide emissions from production storage tanks are on average 0.9 percent higher across the time series compared to the previous *Inventory*. Emissions estimates for 2021 are 4 percent higher than in the previous *Inventory*, which is primarily due to large tanks with flares. The emission changes were due to GHGRP data submission revisions.

Table 3-61: Storage Tanks National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	NO	716	5,336	6,251	5,829	5,594	4,513
Large Tanks w/VRU	NO	3	3	9	2	1	1
Large Tanks w/o Control	24	8	4	9	5	4	2
Small Tanks w/Flares	NO	3	7	9	11	10	11
Small Tanks w/o Flares	12	5	5	4	4	5	5
Malfunctioning Separator Dump Valves	12	13	30	26	21	34	8
Total Emissions	**48**	**748**	**5,386**	**6,309**	**5,871**	**5,649**	**4,539**
Previous Estimate	*47*	*748*	*5,398*	*6,024*	*5,255*	*5439*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Chemical injection Pumps (Recalculation with Updated Data)

Chemical injection pump CH_4 estimates decreased by an average of 19 percent across the time series and decreased by 26 percent in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-62: Chemical Injection Pumps National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	47,425	79,968	108,147	122,967	96,186	85,494	79,712
Previous Estimate	*47,401*	*105,458*	*138,866*	*387,416*	*116,080*	*115,678*	*NA*

NA (Not Applicable)

Produced Water (Recalculation with Updated Data)

Methane estimates from produced water increased by an average of 2 percent across the time series and increased by 4 percent in 2021, compared to the previous *Inventory*. The emission changes were due to Enverus data updates.

Table 3-63: Produced Water National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Produced Water - Regular Pressure Wells	71,854	49,840	73,727	77,370	70,374	71,749	73,665
Produced Water - Low Pressure Wells	20,482	14,207	21,016	22,055	20,061	20,452	20,998
Total Emissions	**92,336**	**64,047**	**94,743**	**99,425**	**90,435**	**92,201**	**94,663**
Previous Estimate	*91,391*	*62,458*	*92,863*	*97,735*	*88,622*	*88,622*	*NA*

NA (Not Applicable)

Associated Gas Flaring (Recalculation with Updated Data)

Associated gas flaring CH_4 emission estimates increased by an average of 2 percent across the time series and increased by 23 percent in 2021, compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-64: Associated Gas Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
220 - Gulf Coast Basin (LA, TX)	901	480	2,379	2,907	3,643	2,136	1,900
360 - Anadarko Basin	452	274	350	90	21	35	30
395 - Williston Basin	2,666	3,405	36,108	58,138	28,176	21,676	18,341

430 - Permian Basin	11,662	7,992	25,286	26,063	12,695	8,178	7,546
"Other" Basins	4,314	2,335	2,089	3,760	2,353	2,790	2,072
Total Emissions	**19,995**	**14,486**	**66,211**	**90,958**	**46,888**	**34,814**	**29,889**
220 - Gulf Coast Basin (LA, TX)	*886*	*490*	*2,440*	*2,991*	*3,692*	*1,864*	*NA*
360 - Anadarko Basin	*447*	*274*	*348*	*88*	*21*	*41*	*NA*
395 - Williston Basin	*2,665*	*3,419*	*36,120*	*48,019*	*23,556*	*18,734*	*NA*
430 - Permian Basin	*11,263*	*7,805*	*25,198*	*27,484*	*13,086*	*5,852*	*NA*
"Other" Basins	*4,369*	*2,347*	*1,992*	*3,563*	*2,295*	*1,802*	*NA*
Previous Estimate	*19,630*	*14,335*	*66,096*	*82,146*	*42,649*	*28,293*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Methane estimates from gas engines decreased by an average of 2 percent across the time series and decreased by 2 percent in 2021, compared to the previous *Inventory*. The emission changes were due to Enverus data updates.

Table 3-65: Gas Engines National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Gas Engines	81,271	69,973	90,773	92,909	88,619	87,040	87,546
Previous Estimate	*81,916*	*71,348*	*91,719*	*93,608*	*89,497*	*89,233*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CO_2 emission estimates are on average 1 percent higher across the time series compared to the previous *Inventory*. Carbon dioxide emissions estimates for 2021 increased by 12 percent compared to the previous *Inventory*. The emission changes were due to GHGRP data submission revisions.

Table 3-66: Miscellaneous Production Flaring National CO_2 Emissions (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
220 - Gulf Coast Basin (LA, TX)	0	103	567	609	654	802	649
395 - Williston Basin	0	71	1,701	3,049	1,307	1,312	1,241
430 - Permian Basin	0	214	1,463	4,312	2,723	2,156	2,709
"Other" Basins	0	398	639	707	427	368	429
Total Emissions	**0**	**786**	**4,370**	**8,678**	**5,110**	**4,638**	**5,028**
Previous Estimate	*0*	*3,008*	*4,307*	*8,225*	*4,679*	*4,154*	*NA*

NA (Not Applicable)

Offshore Production – GOM Federal Waters (Recalculation with Updated Data)

Vented and leak CH_4 emission estimates from offshore production in GOM federal waters decreased by an average of 0.4 percent across the time series and decreased by 8 percent in 2021, compared to the previous *Inventory*. The emission changes were due to updated offshore complex counts from BOEM.

Table 3-67: Offshore Production National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
GOM Federal Waters – Vented	196,769	101,585	112,786	110,263	103,116	102,365	101,546
GOM Federal Waters - Leaks	96,575	103,712	58,938	57,577	53,860	53,395	52,961
Total Emissions	**293,344**	**205,298**	**171,724**	**167,840**	**156,976**	**155,760**	**154,507**
Previous Estimate	*293,204*	*205,207*	*171,910*	*170,190*	*162,543*	*168,798*	*NA*

NA (Not Applicable)

Transportation

Recalculations for the transportation segment have resulted in calculated CH_4 and CO_2 emissions over the time series from this segment that are lower (by less than 0.05 percent) than in the previous *Inventory*.

Refining

Recalculations due to resubmitted GHGRP data in the refining segment have resulted in a decrease in calculated CH_4 emissions by an average of 4.5 percent across the time series and a decrease of 14 percent in 2021, compared to the previous *Inventory*.

Refining CO_2 emission estimates decreased by an average of 8 percent across the time series and decreased by 28 percent in 2021, compared to the previous *Inventory*. This change in emissions is due to GHGRP resubmissions and was largely due to a change in reported flaring CO_2 emissions.

Table 3-68: Refining National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Refining	25,742	29,218	27,804	30,814	25,861	25,366	24,685
Previous Estimate	*26,398*	*29,963*	*30,313*	*35,516*	*31,023*	*29,551*	*NA*

NA (Not Applicable)

Table 3-69: Refining National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	3,023	3,431	2,814	3,523	2,859	2,989	2,836
Total Refining	**3,174**	**3,602**	**2,877**	**3,571**	**2,893**	**3,021**	**2,872**
Previous Estimate	*3,284*	*3,728*	*3,706*	*5,009*	*4,242*	*4,216*	*NA*

NA (Not Applicable)

Planned Improvements

Planned Improvements for 2025 *Inventory*

EPA updated the Enverus data and there were notable increases in the number of wells and completions identified as being hydraulically fractured compared with previous versions of the database. EPA will assess the underlying Enverus data to determine the cause of these changes.

Upcoming Data, and Additional Data that Could Inform the *Inventory*

EPA will assess new data received by the Greenhouse Gas Reporting Program, the Methane Challenge Program, and other relevant programs on an ongoing basis, which may be used to confirm or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the *Inventory*. EPA will also continue to assess studies that include and compare both top-down and bottom-up estimates, and which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in previous stakeholder comments.

Box 3-6: Carbon Dioxide Transport, Injection, and Geological Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications, or is stored geologically. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the *Inventory*, emissions of CO_2 from naturally-occurring CO_2 reservoirs are estimated based

on the specific application.

In the *Inventory*, CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section, 4.15.

For EOR CO_2, as noted in the *2006 IPCC Guidelines*, "At the Tier 1 or 2 methodology levels [EOR CO_2 is] indistinguishable from fugitive greenhouse gas emissions by the associated oil and gas activities." In the U.S. estimates for oil and gas fugitive emissions, the Tier 2 emission factors for CO_2 include CO_2 that was originally injected and is emitted along with other gas from leak, venting, and flaring pathways, as measurement data used to develop those factors would not be able to distinguish between CO_2 from EOR and CO_2 occurring in the produced natural gas. Therefore, EOR CO_2 emitted through those pathways is included in CO_2 estimates in 1B2.

IPCC includes methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO_2. The methodology is based on the principle that the carbon capture and storage system should be handled in a complete and consistent manner across the entire Energy sector. The approach accounts for CO_2 captured at natural and industrial sites as well as emissions from capture, transport, and use. For storage specifically, a Tier 3 methodology is outlined for estimating and reporting emissions based on site-specific evaluations. However, IPCC (IPCC 2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emission estimates for geologic storage.

In the United States, facilities that produce CO_2 for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO_2, exporters of CO_2, facilities that conduct geologic sequestration of CO_2, and facilities that inject CO_2 underground, are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities reporting geologic sequestration of CO_2 to the GHGRP develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and report the amount of CO_2 sequestered using a mass balance approach.

GHGRP data relevant for this *Inventory* estimate consists of national-level annual quantities of CO_2 captured and extracted for EOR applications for 2010 to 2022 and data reported for geologic sequestration from 2016 to 2022.

The amount of CO_2 captured and extracted from natural and industrial sites for EOR applications in 2022 is 36,680 kt (36.7 MMT CO_2 Eq.) 6. The quantity of CO_2 captured and extracted is noted here for information purposes only; CO_2 captured and extracted from industrial and commercial processes is generally assumed to be emitted and included in emissions totals from those processes.

Table 3-70: Quantity of CO_2 Captured and Extracted for EOR Operations (kt CO_2)

Stage	2018	2019	2020	2021	2022
Quantity of CO_2 Captured and Extracted for EOR Operations	48,400	52,100	35,210	35,090	36,680

Several facilities are reporting under GHGRP Subpart RR (Geologic Sequestration of Carbon Dioxide). See Table 3-71 for the number of facilities reporting under Subpart RR, the reported CO_2 sequestered in subsurface geologic formations in each year, and of the quantity of CO_2 emitted from equipment leaks in each year. The quantity of CO_2 sequestered and emitted is noted here for information purposes only; EPA is considering updates to its approach for this source and is seeking feedback as part of this public review draft on potential updates that could be incorporated in future *Inventories*.

Table 3-71: Geologic Sequestration Information Reported Under GHGRP Subpart RR

Stage	2018	2019	2020	2021	2022
Number of Reporting Facilities	5	5	6	9	13
Reported Annual CO_2 Sequestered (kt)	7,662	8,332	6,802	6,947	7,953

Reported Annual CO_2 Emissions from Equipment Leaks (kt)	11	16	13	37	27

3.7 Natural Gas Systems (CRT Source Category 1B2b)

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. This category (1B2b) as defined in the IPCC methodological guidance is for fugitive emissions from natural gas systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from natural gas systems in 2022 were 209.7 MMT CO_2 Eq., a decrease of 17 percent from 1990 and a decrease of 0.3 percent from 2021, both primarily due to decreases in CH_4 emissions. From 2011, emissions decreased by 5 percent, primarily due to decreases in CH_4 emissions. National total dry gas production in the United States increased by 104 percent from 1990 to 2022, increased by 5 percent from 2021 to 2022, and increased by 59 percent from 2011 to 2022. Of the overall greenhouse gas emissions (209.7 MMT CO_2 Eq.), 83 percent are CH_4 emissions (173.1 MMT CO_2 Eq.), 17 percent are CO_2 emissions (36.5 MMT), and less than 0.1 percent are N_2O emissions (0.15 MMT CO_2 Eq.).

Overall, natural gas systems emitted 173.1 MMT CO_2 Eq. (6,183 kt CH_4) of CH_4 in 2022, a 21 percent decrease compared to 1990 emissions, and 1 percent decrease compared to 2021 emissions (see Table 3-72 and Table 3-73). For non-combustion CO_2, a total of 36.5 MMT CO_2 Eq. (36,470 kt) was emitted in 2022, a 12 percent increase compared to 1990 emissions, and a 2 percent increase compared to 2021 levels. The 2022 N_2O emissions were estimated to be 0.15 MMT CO_2 Eq. (0.57 kt N_2O), a 3205 percent increase compared to 1990 emissions, and a 1104 percent increase compared to 2021 levels.

The 1990 to 2022 emissions trend is not consistent across segments or gases. Overall, the 1990 to 2022 decrease in CH_4 emissions is due primarily to the decrease in emissions from the following segments: distribution (70 percent decrease), transmission and storage (38 percent decrease), processing (37 percent decrease), and exploration (97 percent decrease). Over the same time period, the production segment saw increased CH_4 emissions of 38 percent (with onshore production emissions increasing 16 percent, offshore production emissions decreasing 86 percent, and gathering and boosting [G&B] emissions increasing 108 percent), and post-meter emissions increasing by 65 percent. The 1990 to 2022 increase in CO_2 emissions is primarily due to an increase in CO_2 emissions in the production segment, where emissions from flaring have increased over time.

Methane and CO_2 emissions from natural gas systems include those resulting from normal operations, routine maintenance, and system upsets. Emissions from normal operations include natural gas engine and turbine uncombusted exhaust, flaring, and leak emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions. Emissions of N_2O from flaring activities are included in the *Inventory*, with most of the emissions occurring in the processing and production segments. Note, CO_2 emissions exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in Section 3.1.

Each year, some estimates in the *Inventory* are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2022) to ensure that the trend is representative of changes in emissions. Recalculations in natural gas systems in this year's *Inventory* include:

- Methodological updates to transmission compressor station activity data, completions and workovers, and underground natural gas storage well events.
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions.
- Recalculations due to updated well counts and production data from Enverus.

The Recalculations Discussion section below provides more details on the updated methods.

Below is a characterization of the six emission subcategories of natural gas systems: exploration, production (including gathering and boosting), processing, transmission and storage, distribution, and post-meter. Each of the segments is described and the different factors affecting CH_4, CO_2, and N_2O emissions are discussed.

Exploration. Exploration includes well drilling, testing, and completion. Emissions from exploration accounted for 0.1 percent of CH_4 emissions and 0.1% of CO_2 emissions from natural gas systems in 2022. Well completions accounted for approximately 90 percent of CH_4 emissions from the exploration segment in 2022, with the rest resulting from well testing and drilling. Well completion flaring emissions account for most of the CO_2 emissions. Methane emissions from exploration decreased by 97 percent from 1990 to 2022, with the largest decreases coming from hydraulically fractured gas well completions without reduced emissions completions (RECs). Methane emissions from exploration increased 58 percent from 2021 to 2022 due to increases in emissions from hydraulically fractured well completions (both non-REC with flaring and REC with venting). Methane emissions from exploration were highest from 2006 to 2008. Carbon dioxide emissions from exploration decreased by 94 percent from 1990 to 2022 primarily due to decreases in hydraulically fractured gas well completions. Carbon dioxide emissions from exploration increased by 14 percent from 2020 to 2021 due to increases in emissions from hydraulically fractured gas well completions (REC with flaring). Carbon dioxide emissions from exploration were highest from 2006 to 2008. Nitrous oxide emissions from exploration decreased 95 percent from 1990 to 2022 and increased 74 percent from 2021 to 2022.

Production (including gathering and boosting). In the production segment, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, and from well-site equipment and activities such as pneumatic controllers, tanks and separators, and liquids unloading. Gathering and boosting emission sources are included within the production sector. The gathering and boosting sources include gathering and boosting stations (with multiple emission sources on site) and gathering pipelines. The gathering and boosting stations receive natural gas from production sites and transfer it, via gathering pipelines, to transmission pipelines or processing facilities (custody transfer points are typically used to segregate sources between each segment). Boosting processes include compression, dehydration, and transport of gas to a processing facility or pipeline. Emissions from production (including gathering and boosting) accounted for 52 percent of CH_4 emissions and 23 percent of CO_2 emissions from natural gas systems in 2022. Emissions from gathering and boosting and pneumatic controllers in onshore production accounted for most of the production segment CH_4 emissions in 2022. Within gathering and boosting, the largest sources of CH_4 are compressor exhaust slip, compressor venting and leaks, and tanks. Flaring emissions account for most of the CO_2 emissions from production, with the highest emissions coming from flare stacks at gathering stations, miscellaneous onshore production flaring, and tank flaring. Methane emissions from production increased by 38 percent from 1990 to 2022, due primarily to increases in emissions from pneumatic controllers (due to an increase in the number of controllers, particularly in the number of intermittent bleed controllers) and increases in emissions from compressor exhaust slip in gathering and boosting. Methane emissions from production decreased 3 percent from 2021 to 2022 due to decreases in emissions from pneumatic controllers and liquids unloading. Carbon dioxide emissions from production increased by approximately a factor of 2.6 from 1990 to 2022 due to increases in emissions at flare stacks in gathering and boosting and miscellaneous onshore production flaring and decreased 8 percent from 2021 to 2022 due primarily to decreases in emissions at flare stacks in miscellaneous onshore production flaring and tank venting. Nitrous oxide emissions from production were 36.9 times higher in 2022 than in 1990 and 17.5 times higher in 2022 than in 2021. The increase in N_2O emissions from 1990 to 2022 and from 2021 to 2022 is primarily due to increases in emissions from condensate tank flaring.

Processing. In the processing segment, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Methane emissions from compressors, including compressor seals, are the primary emission source from this stage. Most of the CO_2 emissions come from acid gas removal (AGR) units, which are designed to remove CO_2 from natural gas. Processing plants accounted for 9 percent of CH_4 emissions and 73 percent of CO_2 emissions from natural gas systems. Methane emissions from processing decreased by 37 percent from 1990 to 2022 as emissions from compressors (leaks and venting) and equipment leaks decreased; and increased 7 percent from 2021 to 2022 due to increased emissions from gas engines. Carbon dioxide emissions from processing decreased by 6 percent from 1990 to 2022,

due to a decrease in AGR, and increased 4 percent from 2021 to 2022 due to increased emissions from flaring emissions at processing plants. Nitrous oxide emissions increased 116 percent from 2021 to 2022.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities are used to move the gas throughout the U.S. transmission system. Leak CH_4 emissions from these compressor stations and venting from pneumatic controllers account for most of the emissions from this stage. Uncombusted compressor engine exhaust and pipeline venting are also sources of CH_4 emissions from transmission. Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Leak and venting emissions from compressors are the primary contributors to CH_4 emissions from storage. Emissions from liquefied natural gas (LNG) stations and terminals are also calculated under the transmission and storage segment. Methane emissions from the transmission and storage segment accounted for approximately 23 percent of methane emissions from natural gas systems, while CO_2 emissions from transmission and storage accounted for 3 percent of the CO_2 emissions from natural gas systems. CH_4 emissions from this source decreased by 38 percent from 1990 to 2022 due to reduced pneumatic device and compressor station emissions (including emissions from compressors and leaks) and decreased 1 percent from 2021 to 2022 due to decreased emissions from pipeline venting transmission compressors. CO_2 emissions from transmission and storage were 6.6 times higher in 2022 than in 1990, due to increased emissions from LNG export terminals, and increased by 36 percent from 2021 to 2022, also due to LNG export terminals and flaring (both transmission and storage). The quantity of LNG exported from the United States increased by a factor of 74 from 1990 to 2022, and by 9 percent from 2021 to 2022. LNG emissions are about 1 percent of CH_4 and 86 percent of CO_2 emissions from transmission and storage in year 2022. Nitrous oxide emissions from transmission and storage increased by 405 percent from 1990 to 2022 and increased by 177 percent from 2021 to 2022.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. There were 1,352,384 miles of distribution mains in 2022, an increase of 408,227 miles since 1990 (PHMSA 2022). Distribution system emissions, which accounted for 9 percent of CH_4 emissions from natural gas systems and less than 0.1 percent of CO_2 emissions from natural gas systems, result mainly from leak emissions from pipelines and stations. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced both CH_4 and CO_2 emissions from this stage, as have station upgrades at metering and regulating (M&R) stations. Distribution system CH_4 emissions in 2022 were 70 percent lower than 1990 levels and 1 percent lower than 2021 emissions. Distribution system CO_2 emissions in 2022 were 70 percent lower than 1990 levels and 1 percent lower than 2021 emissions. Annual CO_2 emissions from this segment are less than 0.1 MMT CO_2 Eq. across the time series.

Post-Meter. Post-meter includes leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles. Leak emissions from residential appliances and industrial facilities and power plants account for the majority of post-meter CH_4 emissions. Methane emissions from the post-meter segment accounted for approximately 8 percent of emissions from natural gas systems in 2022. Post-meter CH_4 emissions increased by 65 percent from 1990 to 2022 and increased by 3 percent from 2021 to 2022, due to increases in the number of residential houses using natural gas and increased natural gas consumption at industrial facilities and power plants. CO_2 emissions from post-meter account for less than 0.01 percent of total CO_2 emissions from natural gas systems.

Total greenhouse gas emissions from the six subcategories within natural gas systems are shown in MMT CO_2 Eq. in Table 3-72. Total CH_4 emissions for these same segments of natural gas systems are shown in MMT CO_2 Eq. (Table 3-73) and kt (Table 3-74). Most emission estimates are calculated using a net emission approach. However, a few sources are still calculated with a potential emission approach. Reductions data are applied to those sources. In 2022, 2.6 MMT CO_2 Eq. CH_4 is subtracted from production segment emissions, 4.3 MMT CO_2 Eq. CH_4 is subtracted from the transmission and storage segment, and 0.1 MMT CO_2 Eq. CH_4 is subtracted from the distribution segment to calculate net emissions. More disaggregated information on potential emissions, net

emissions, and reductions data is available in Annex 3.6, Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems.

Table 3-72: Total Greenhouse Gas Emissions (CH_4, CO_2, and N_2O) from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	7.3	22.3	2.9	2.3	0.3	0.1	0.2
Production	68.4	97.9	114.1	114.5	105.8	101.5	98.3
Processing	52.2	31.8	36.3	40.4	39.3	39.7	41.8
Transmission and Storage	64.2	46.2	41.7	41.8	43.1	40.7	40.7
Distribution	51.0	28.5	15.6	15.5	15.5	15.3	15.3
Post-Meter	8.1	9.6	12.5	12.8	13.0	13.0	13.4
Total	**251.2**	**236.5**	**223.0**	**227.3**	**217.0**	**210.4**	**209.7**

Note: Totals may not sum due to independent rounding.

Table 3-73: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	6.7	19.6	2.6	2.1	0.2	0.1	0.2
Production	65.2	93.4	104.9	103.6	96.7	92.2	89.7
Onshore Production	*39.9*	*64.4*	*60.5*	*58.0*	*53.1*	*48.3*	*46.2*
Gathering and Boosting	*20.5*	*27.0*	*43.6*	*44.8*	*42.7*	*43.3*	*42.8*
Offshore Production	*4.8*	*2.0*	*0.9*	*0.8*	*0.9*	*0.6*	*0.6*
Processing	23.9	13.0	13.5	14.2	13.8	14.2	15.1
Transmission and Storage	64.0	46.0	41.2	40.5	41.1	39.8	39.6
Distribution	50.9	28.5	15.6	15.5	15.5	15.3	15.2
Post-Meter	8.1	9.6	12.5	12.8	13.0	13.0	13.4
Total	**218.8**	**210.1**	**190.3**	**188.7**	**180.3**	**174.6**	**173.1**

Note: Totals may not sum due to independent rounding.

Table 3-74: CH_4 Emissions from Natural Gas Systems (kt)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	238	700	93	75	7	4	6
Production	2,328	3,335	3,748	3,701	3,453	3,293	3,202
Onshore Production	*1,424*	*2,299*	*2,162*	*2,073*	*1,895*	*1,726*	*1,650*
Gathering and Boosting	*733*	*963*	*1,556*	*1,601*	*1,527*	*1,545*	*1,528*
Offshore Production	*170*	*73*	*31*	*28*	*32*	*22*	*23*
Processing	853	463	483	507	495	507	541
Transmission and Storage	2,285	1,645	1,470	1,448	1,468	1,421	1,413
Distribution	1,819	1,018	556	554	553	547	544
Post-Meter	290	344	445	457	463	464	477
Total	**7,813**	**7,505**	**6,795**	**6,741**	**6,439**	**6,235**	**6,183**

Note: Totals may not sum due to independent rounding.

Table 3-75: CO_2 Emissions from Natural Gas Systems (MMT)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	0.6	2.7	0.3	0.2	0.1	+	+
Production	3.2	4.6	9.1	10.8	9.1	9.3	8.6
Processing	28.3	18.8	22.8	26.2	25.5	25.5	26.7
Transmission and Storage	0.2	0.2	0.5	1.2	2.0	0.9	1.2
Distribution	0.1	+	+	+	+	+	+
Post-Meter	+	+	+	+	+	+	+
Total	**32.4**	**26.3**	**32.8**	**38.5**	**36.7**	**35.8**	**36.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-76: CO_2 Emissions from Natural Gas Systems (kt)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	619	2,710	325	249	97	32	37
Production	3,236	4,554	9,118	10,844	9,102	9,331	8,558
Processing	28,338	18,836	22,769	26,189	25,471	25,525	26,672
Transmission and Storage	179	181	537	1,224	2,030	874	1,185
Distribution	54	30	17	16	16	16	16
Post-Meter	1	1	2	2	2	2	2
Total	**32,427**	**26,312**	**32,768**	**38,525**	**36,719**	**35,780**	**36,470**

Note: Totals may not sum due to independent rounding.

Table 3-77: N_2O Emissions from Natural Gas Systems (Metric Tons CO_2 Eq.)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	518	1,708	148	114	46	15	27
Production	3,853	5,467	5,768	6,157	3,687	8,115	142,002
Processing	NO	2,977	3,002	5,082	4,353	4,083	8,808
Transmission and Storage	228	276	205	553	943	415	1,149
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**4,599**	**10,428**	**9,123**	**11,906**	**9,029**	**12,628**	**151,986**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Table 3-78: N_2O Emissions from Natural Gas Systems (Metric Tons N_2O)

Segment	1990	2005	2018	2019	2020	2021	2022
Exploration	2.0	6.4	0.6	0.4	0.2	0.1	0.1
Production	14.5	20.6	21.8	23.2	13.9	30.6	535.9
Processing	NO	11.2	11.3	19.2	16.4	15.4	33.2
Transmission and Storage	0.9	1.0	0.8	2.1	3.6	1.6	4.3
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**17.4**	**39.3**	**34.4**	**44.9**	**34.1**	**47.7**	**573.5**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.6 for the full time series of emissions data, activity data, and emission factors, and additional information on methods and data sources—for example, the specific years of reporting data from EPA's GHGRP that are used to develop certain factors.

This section provides a general overview of the methodology for natural gas system emission estimates in the *Inventory*, which involves the calculation of CH_4, CO_2, and N_2O emissions for over 100 emissions sources (i.e., equipment types or processes), and then the summation of emissions for each natural gas segment.

The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For most sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and emission reduction data to calculate net emissions. The estimates are developed with an IPCC Tier 2 approach. Tier 1 approaches are not used.

Emission Factors. Key references for emission factors for CH_4 and CO_2 emissions from the U.S. natural gas industry include a 1996 study published by the Gas Research Institute (GRI) and EPA (GRI/EPA 1996), EPA's GHGRP (EPA 2023b), and others.

The 1996 GRI/EPA study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating segments of the U.S. natural gas system. The GRI/EPA study was based on a combination of process engineering studies, collection of activity data, and measurements at representative natural gas facilities conducted in the early 1990s. Year-specific natural gas CH_4 compositions are calculated using U.S. Department of Energy's Energy Information Administration (EIA) annual gross production data for National Energy Modeling System (NEMS) oil and gas supply module regions in conjunction with data from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001). These year-specific CH_4 compositions are applied to emission factors, which therefore may vary from year to year due to slight changes in the CH_4 composition of natural gas for each NEMS region.

GHGRP Subpart W data were used to develop CH_4, CO_2, and N_2O emission factors for many sources in the *Inventory*. In the exploration and production segments, GHGRP data were used to develop emission factors used for all years of the time series for well testing, gas well completions and workovers with and without hydraulic fracturing, pneumatic controllers and chemical injection pumps, condensate tanks, liquids unloading, miscellaneous flaring, gathering and boosting pipelines, and certain sources at gathering and boosting stations. In the processing segment, for recent years of the time series, GHGRP data were used to develop emission factors for leaks, compressors, flares, dehydrators, and blowdowns/venting. In the transmission and storage segment, GHGRP data were used to develop factors for all years of the time series for LNG stations and terminals and transmission pipeline blowdowns, and for pneumatic controllers for recent years of the time series.

Other data sources used for CH_4 emission factors include Zimmerle et al. (2015) for transmission and storage station leaks and compressors, GTI (2009 and 2019) for commercial and industrial meters, Lamb et al. (2015) for recent years for distribution pipelines and meter/regulator stations, Zimmerle et al. (2019) for gathering and boosting stations, Bureau of Ocean Energy Management (BOEM) reports, and Fischer et al. (2019) and IPCC (2019) for post-meter emissions.

For CO_2 emissions from sources in the exploration, production, and processing segments that use emission factors not directly calculated from GHGRP data, data from the 1996 GRI/EPA study and a 2001 GTI publication were used to adapt the CH_4 emission factors into related CO_2 emission factors. For sources in the transmission and storage segment that use emission factors not directly calculated from GHGRP data, and for sources in the distribution segment, data from the 1996 GRI/EPA study and a 1993 GTI publication were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. CO_2 emissions from post-meter sources (commercial, industrial and vehicles) were estimated using default emission factors from IPCC (2019). Carbon dioxide emissions from post-meter residential sources are included in fossil fuel combustion data.

Flaring N_2O emissions were estimated for flaring sources using GHGRP data.

See Annex 3.6 for more detailed information on the methodology and data used to calculate CH_4, CO_2, and N_2O emissions from natural gas systems.

Activity Data. Activity data were taken from various published data sets, as detailed in Annex 3.6. Key activity data sources include data sets developed and maintained by EPA's GHGRP (EPA 2023b); Enverus (Enverus 2023); BOEM; Federal Energy Regulatory Commission (FERC); EIA; the Natural Gas STAR and Methane Challenge Programs annual data; Oil and Gas Journal; and PHMSA.

For a few sources, recent direct activity data are not available. For these sources, either 2021 data were used as a proxy for 2022 data, or a set of industry activity data drivers was developed and used to calculate activity data over the time series. Drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. More information on activity data and drivers is available in Annex 3.6.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.6.

Calculating Net Emissions. For most sources, net emissions are calculated directly by applying emission factors to activity data. Emission factors used in net emission approaches reflect technology-specific information and take into account regulatory and voluntary reductions. However, for production, transmission and storage, and distribution, some sources are calculated using potential emission factors, and CH_4 that is not emitted is deducted from the total CH_4 potential estimates. To account for use of such technologies and practices that result in lower emissions but are not reflected in "potential" emission factors, data are collected on both regulatory and voluntary reductions. Regulatory actions addressed using this method include EPA National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents. Voluntary reductions included in the *Inventory* are those reported to Natural Gas STAR and Methane Challenge for certain sources.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. GHGRP data available (starting in 2011) and other recent data sources have improved estimates of emissions from natural gas systems. To develop a consistent time series, for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2010 by interpolating activity data or emission factors or both between 1992 and 2011 data points. Information on time-series consistency for sources updated in this year's *Inventory* can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For detailed documentation of methodologies, please see Annex 3.5.

The United States reports data to the UNFCCC using this *Inventory* report along with Common Reporting Tables (CRTs). This note is provided for those reviewing the CRTs: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRT 1.B.2. Disaggregating flaring and venting estimates across the *Inventory* would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

Uncertainty

EPA has conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize the uncertainty for natural gas systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* (*2018 uncertainty memo*) and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates* (*2021*

uncertainty memo).[79]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from natural gas systems for the current *Inventory*. For the CH_4 uncertainty analysis, EPA focused on the 17 highest-emitting sources for the year 2022, which together emitted 75 percent of methane from natural gas systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. For the CO_2 uncertainty analysis, EPA focused on the three highest-emitting sources for the year 2022, which together emitted 81 percent of CO_2 from natural gas systems in 2022, and extrapolated the estimated uncertainty for the remaining sources. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future Inventories. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. For emission factors that are derived from methane emissions measurement studies, the PDFs are commonly determined to be lognormally distributed (GRI/EPA 1996; GTI 2001; GTI 2009; Lamb et al. 2015; Zimmerle et al. 2015; Fischer et al. 2018; GTI 2019). For activity data that are derived from national datasets, the PDFs are set to a uniform distribution (see 2018 and 2021 uncertainty memos). Many emission factors and activity factors are calculated using Subpart W data, and for these, the @RISK add-in determines the best fitting PDF (e.g., lognormal, gaussian), based on bootstrapping of the underlying data (see 2018 and 2021 uncertainty memos). The IPCC guidance notes that in using this Approach 2 method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. The understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2022, using the IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-79. Natural gas systems CH_4 emissions in 2022 were estimated to be between 141.2 and 203.0 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems CO_2 emissions in 2022 were estimated to be between 31.9 and 42.1 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems N_2O emissions in 2022 were estimated to be between 0.13 and 0.18 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., liquids unloading with plunger lifts and reduced emissions completions were not used early in the time series and cast iron distribution mains were more prevalent than plastic mains in early years). Transmission and gas processing compressor leak and vent emissions were also higher in the early years of the time series.

Table 3-79: Approach 2 Quantitative Uncertainty Estimates for CH_4 and Non-combustion CO_2 Emissions from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Natural Gas Systems	CH_4	173.1	141.2	203.0	-18%	+17%

[79] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Natural Gas Systems	CO_2	36.5	31.9	42.1	-12%	+15%
Natural Gas Systems	N_2O	0.15	0.13	0.18	-12%	+15%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo simulation analysis conducted for the year 2022 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in Table 3-73 and Table 3-74.

QA/QC and Verification Discussion

In order to ensure the quality of the emission estimates for natural gas systems, general (IPCC Tier 1) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8.

The natural gas systems emission estimates in the *Inventory* are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the *Inventory* are consistent with current industry practices. The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.[80]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current *Inventory*. EPA held a stakeholder webinar in October of 2023. EPA released memos detailing updates under consideration and requesting stakeholder feedback.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the *Inventory*. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of *Inventory* estimates. In the past few years, EPA has reviewed and, in many cases, incorporated data from these data sources. The second type of study can provide general indications of potential over- and under-estimates. In addition, in recent years information from top-down studies has been directly incorporated to quantify emissions from well blowouts.

A key challenge in using these types of studies to assess *Inventory* results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the *Inventory* and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level *Inventory* with measurement results that may be at other spatial and temporal scales, EPA has developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[81] The most recent version of the gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018* estimates for the years 2012 to 2018. The gridded inventory improves efforts to compare results of this *Inventory* with atmospheric studies.

[80] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[81] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting and presented information to stakeholders regarding the updates under consideration. In November 2023, EPA released draft memoranda that discussed changes under consideration and requested stakeholder feedback on those changes. EPA then released final memoranda documenting the methodology implemented in the current Inventory.[82] Memoranda cited in the Recalculations Discussion below are: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Transmission Compressor Station Activity (*Transmission Station Activity* memo), Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Completion and Workover Emissions (*Completions and Workovers* memo), and Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Underground Natural Gas Storage Well Emission Events (*Storage Well Events* memo).

EPA evaluated relevant information available and made several updates to the *Inventory*, including for transmission compressor stations, completions and workovers, and underground natural gas storage wells. General information for these source specific recalculations are presented below and details are available in the *Transmission Station Activity*, *Completions and Workovers*, and *Storage Well Events* memos, including additional considerations for the updates.

In addition to the updates to the sources mentioned above, for certain sources, CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. The emissions changes were mostly due to GHGRP data submission revisions. These sources are discussed below and include pneumatic controllers, well pad equipment leaks, condensate tanks, liquids unloading, gas engines (in production segment), miscellaneous production flaring, gathering and boosting (G&B) station blowdowns, G&B pneumatic controllers, G&B yard piping, G&B acid gas removal units (AGRU), natural gas processing flares, and transmission pipeline venting.

The combined impact of revisions to 2021 natural gas systems CH_4 emissions, compared to the previous *Inventory*, is a decrease from 181.4 to 174.6 MMT CO_2 Eq. (6.8 MMT CO_2 Eq., or 4 percent). The recalculations resulted in an average increase in the annual CH_4 emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 1.9 MMT CO_2 Eq., or 0.8 percent.

The combined impact of revisions to 2021 natural gas systems CO_2 emissions, compared to the previous *Inventory*, is a decrease from 36.2 MMT to 35.8 MMT, or 1.1 percent. The recalculations resulted in an average increase in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 0.4 MMT CO_2 Eq., or 1.5 percent.

The combined impact of revisions to 2021 natural gas systems N_2O emissions, compared to the previous *Inventory*, is an increase from 7.6 kt CO_2 Eq. to 12.6 kt CO_2 Eq., or 65 percent. The recalculations resulted in an average increase in emission estimates across the 1990 through 2021 time series, compared to the previous *Inventory*, of 10.4 percent.

In Table 3-80 and Table 3-81 below are categories in natural gas systems with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2021 to the current (recalculated) estimate for 2021. No changes made to N_2O estimates resulted in a change greater than 0.05 MMT CO_2 Eq. For more information, please see the Recalculations Discussion below.

[82] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2022) *Inventory* are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Table 3-80: Recalculations of CO_2 in Natural Gas Systems (MMT CO_2)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO_2 due to Recalculations	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***+***	**+**	**+**
Gas Well Completions	*+*	+	+
Production	***9.1***	**9.3**	**8.6**
Gas Well Workovers	*+*	+	+
Pneumatic Controllers	*0.1*	+	+
Well Pad Equipment Leaks	*+*	0.1	0.1
Chemical Injection Pumps	*+*	+	+
Misc. Onshore Production Flaring	*1.0*	1.1	0.7
Condensate Tanks	*0.9*	1.1	0.6
G&B Station - AGRU	*2.3*	2.2	2.0
Processing	***26.1***	**25.5**	**26.7**
Flares	*7.4*	6.9	8.5
Transmission and Storage	***0.9***	**0.9**	**1.2**
Transmission Compressor Station Leaks and Venting	*0.1*	0.1	0.1
Storage Wells	*+*	+	+
Distribution	***+***	**+**	**+**
Post-Meter	***+***	**+**	**+**
Total	**36.2**	**35.8**	**36.5**

+ Does not exceed 0.05 MMT CO_2.

Note: Totals may not sum due to independent rounding.

Table 3-81: Recalculations of CH_4 in Natural Gas Systems (MMT CO_2 Eq.)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO_2 due to Recalculations	*Previous Estimate Year 2021, 2023 Inventory*	Current Estimate Year 2021, 2024 *Inventory*	Current Estimate Year 2022, 2024 *Inventory*
Exploration	***0.2***	**0.1**	**0.2**
Gas Well Completions	*0.2*	0.1	0.2
Production	***94.1***	**92.2**	**89.7**
Gas Well Workovers	*0.2*	0.04	0.05
Well Pad Equipment Leaks	*9.6*	9.4	10.8
Pneumatic Controllers	*21.3*	20.9	18.0
Condensate Tanks	*1.2*	1.2	1.1
Liquids Unloading	*3.4*	2.8	2.4
Gas Engines	*5.5*	5.3	5.3
G&B Stations – Station Blowdowns	*1.2*	1.0	0.9
G&B Stations – Pneumatic Controllers	*0.7*	0.6	0.5
G&B Station – Yard Piping	*2.6*	2.7	2.8
Processing	***14.3***	**14.2**	**15.1**
Flares	*0.8*	0.8	0.9
Transmission and Storage	***44.5***	**39.8**	**39.6**
Transmission Compressor Station Leaks and Venting	*25.9*	21.3	21.5
Storage Wells	*0.3*	0.3	0.3
Pipeline Venting	*4.8*	4.6	3.7
Distribution	***15.3***	**15.3**	**15.2**
Post-Meter	***13.0***	**13.0**	**13.4**
Total	***181.4***	**174.6**	**173.1**

Note: Totals may not sum due to independent rounding.

Exploration

HF Completions (Methodological Update)

EPA updated the calculation methodology for HF completions to use basin-level HF completion counts from Enverus and basin-specific activity factors and emission factors calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national annual average activity and emission factors calculated using Subpart W data were applied to national completion counts to estimate HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 through RY2022. For basin-level HF completion event counts, EPA used Enverus data for 1990 to 2010 and Subpart W for 2011 forward. For the fraction of completions in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well completions were non-REC for 1990 to 2000. The previous *Inventory* also assumed that 10 percent of HF completions were non-REC with flaring from 1990 to 2010 (based on national Subpart W data for RY2011 and RY2012); EPA updated this value using basin-specific Subpart W data for RY2011 and RY2012. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data and used linear interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

Comparing the final completion emissions and those presented at the October 2023 webinar and in the November 2023 *Completions and Workovers* memo, the final estimates are higher for certain completion categories. These emissions increases are due not to the basin-level methodology changes discussed here but rather to changes in the Enverus dataset. EPA applied the same data processing steps to Enverus data in the fall of 2023 as it did for the previous Enverus data analysis (conducted in 2021) and data changes led to many more completions being classified as HF completions.

As a result of this methodological update, CH_4 emissions estimates for HF completions are on average 55 percent higher across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 54 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 134 percent in 1998 with an average increase of 92 percent over the 1990 through 2010 time period. CH_4 emissions decreased or were similar for 2011 forward and the largest decrease between the updates and the previous *Inventory* is 54 percent in 2021. CH_4 emissions increased on average across the time series, but particularly in earlier years due to gas well HF completions that were non-REC with venting, particularly in the Appalachian basin (Eastern Overthrust) [basin 160a]. The Appalachian basin (Eastern Overthrust) had a large number of gas well HF completion events that were non-REC with venting and the highest EF of any basin. The update resulted in CO_2 emissions estimates that are on average 54 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 3 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 141 percent in 1996, and the largest decrease between the updates and the previous *Inventory* is 44 percent in 2013. CO_2 emissions increased predominantly due to non-REC with flaring events in the Appalachian basin (basin 160A) and the East Texas basin (basin 260); these two basins had the highest EFs of any basin.

Table 3-82: HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	187,841	590,423	1,210	678	75	166	83
HF Completions – Non-REC with Flaring	3,112	11,791	652	399	154	31	1,605
HF Completions - REC with Venting	NO	6,710	28,946	18,150	4,594	2,487	3,376

HF Completions - REC with Flaring	NO	2,238	1,345	1,148	634	127	190
Total Emissions	**190,954**	**611,162**	**32,154**	**20,375**	**5,458**	**2,811**	**5,253**
Previous Estimate	*111,265*	*345,098*	*32,147*	*20,002*	*5,220*	*6,111*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-83: HF Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Completions – Non-REC with Venting	15	50	+	+	+	+	+
HF Completions – Non-REC with Flaring	472	2,023	57	43	10	2	5
HF Completions - REC with Venting	NO	4	3	+	+	+	+
HF Completions - REC with Flaring	NO	496	233	199	87	13	31
Total Emissions	**487**	**2,573**	**293**	**243**	**97**	**15**	**36**
Previous Estimate	*289*	*1,418*	*290*	*214*	*96*	*15*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Non-HF Completions (Methodological Update)

EPA updated the activity data sources and calculation methodology for non-HF completions to use basin-level non-HF completion counts from Enverus and basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., vented, flared). Previously, national non-HF completion counts and national annual average activity and emission factors calculated using historical data analyses, and Subpart W data were applied to estimate non-HF gas well completion emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. The factors were year-specific for reporting year (RY) 2011 through RY2022. For basin-level non-HF gas well completion event counts, EPA used Enverus data across the time series. For the fraction of completions in each control category, EPA implemented at the basin level the previous *Inventory's* approach and the percent of non-HF gas well completions that are vented in 2011 is applied to all prior years. For 2011 to 2022, EPA determined the percent contribution of each control category directly from Subpart W data for each basin. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for non-HF completions are on average 419 percent higher across the time series than in the previous *Inventory*. The 2021 CH_4 estimate is 43 percent higher than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 1,533 percent in 1991, and the largest decrease between the updates and the previous *Inventory* is 63 percent in 2018. Methane emissions increased primarily due to gas well non-HF completions that were vented. The Appalachian basin (Eastern Overthrust) [basin 160a] and the Appalachian basin (basin 160) had many non-HF completion events that were vented and average EFs more than 2 times higher than the national average across the 1990-2022 time series. The update resulted in CO_2 emissions estimates that are on average 1,312 percent higher across the time series than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 7,331 percent higher than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 7,331 percent in 2021, and the largest decrease between the updates and the previous *Inventory* is 47 percent in 2018. The increase in CO_2 emissions is due to non-HF completions that were flared, primarily in the Gulf Coast basin (basin 220). The Gulf Coast basin had the highest fraction of non-HF completions that were flared of any basin.

Table 3-84: Non-HF Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Completions - vented	44,362	84,955	79	319	1,548	284	159
Non-HF Completions - flared	547	545	113	+	NO	98	NO
Total Emissions	**44,909**	**85,500**	**192**	**320**	**1,548**	**381**	**159**
Previous Estimate	*5,736*	*10,363*	*513*	*796*	*2,659*	*267*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)

Table 3-85: Non-HF Completions National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Completions - vented	1,398	3,531	1	8	197	8	549
Non-HF Completions - flared	127,316	126,743	15,699	42	NO	16,449	NO
Total Emissions	**128,714**	**130,274**	**15,700**	**50**	**197**	**16,457**	**549**
Previous Estimate	*4,862*	*8,784*	*29,834*	*81*	*364*	*221*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Production

HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., non-reduced emission completion (REC) with venting, non-REC with flaring, REC with venting, REC with flaring). Previously, national HF workover counts calculated using analyses for NSPS OOOO (i.e., 1 percent of HF gas wells were worked over annually) and national annual average emission factors calculated using Subpart W data were applied to estimate HF gas well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, instead of applying a 1 percent workover rate to HF gas wells, EPA developed year- and basin-specific Subpart W AFs for 2015 forward that represent the number of HF workovers per gas well. Year 2015 Subpart W AFs were applied to all prior years for each basin. For the fraction of workovers in each control subcategory, EPA retained the previous *Inventory's* assumption that all HF gas well workovers were non-REC for 1990 to 2000. The previous Inventory also assumed that 10 percent of HF workovers were non-REC with flaring from 1990 to 2010; EPA updated this value using basin-specific data from Subpart W. For 2011 forward, EPA determined the percent contribution of each control category directly from Subpart W data at the basin-level. EPA used linear interpolation for interpolation between 2000 and 2011 to determine the percent of gas wells with RECs. EPA developed year-and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for HF workovers are on average 43 percent lower across the time series than in the previous *Inventory*. The 2021 CH_4 emissions estimate is 94 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CH_4 emissions is 5 percent in 1990, and the largest decrease between the updates and the previous *Inventory* is 99 percent in 2019. The update resulted in CO_2 emissions estimates that are on average 60 percent lower than in the previous *Inventory*. The 2021 CO_2 emissions estimate is 67 percent lower than in the previous *Inventory*. The largest increase between the updates and the previous *Inventory* for CO_2 emissions is 53 percent in 2013, and the

largest decrease between the updates and the previous *Inventory* is 99 percent in 2019. The decrease in emissions for both CH_4 and CO_2 was primarily due to the change in calculation method for workover counts. HF gas well workover counts decreased by an average of 73 percent across the 1990 through 2021 time series compared to the previous *Inventory*.

Table 3-86: HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	22,198	37,917	114	96	4	17	35
HF Workovers – Non-REC with Flaring	242	483	29	2	1	+	19
HF Workovers - REC with Venting	NO	231	1,667	73	229	457	113
HF Workovers - REC with Flaring	NO	+	6	4	1	2	17
Total Emissions	**22,440**	**38,632**	**1,816**	**174**	**234**	**476**	**185**
Previous Estimate	*21,427*	*57,972*	*19,594*	*13,612*	*6,771*	*8,144*	*NA*

+ Does not exceed 0.5 mt.
NO (Not Occurring)
NA (Not Applicable)

Table 3-87: HF Workovers National CO_2Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
HF Workovers – Non-REC with Venting	1	2	+	+	+	+	+
HF Workovers – Non-REC with Flaring	32	67	2	+	+	+	+
HF Workovers - REC with Venting	NO	+	+	+	+	+	+
HF Workovers - REC with Flaring	NO	+	1	+	+	+	3
Total Emissions	**33**	**69**	**4**	**1**	**+**	**+**	**3**
Previous Estimate	*56*	*165*	*99*	*86*	*8*	*1*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Non-HF Workovers (Methodological Update)

EPA updated the activity data source and calculation methodology for non-HF workovers to use basin-specific activity factors and emission factors, calculated from Subpart W data for each control category (i.e., vented, flared). Previously, national annual average activity and emission factors calculated using historical data analyses and Subpart W data were applied along with national gas well counts to estimate non-HF gas well workover emissions. In this update, EPA developed national emission estimates by summing calculated basin-level total emission estimates. The *Completions and Workovers* memo presents additional information and considerations for this update.

EPA calculated basin-specific activity factors and CH_4 and CO_2 emission factors for all basins that reported Subpart W data. For basin-level workover counts, EPA developed year-specific Subpart W AFs for 2015 forward. Year 2015 Subpart W data was applied to prior years for each basin. For the fraction of workovers in each control subcategory, EPA applied year- and basin-specific AFs for 2011 forward, retained the previous *Inventory's* assumption that all non-HF workovers were vented in 1990 to 1992, and used linear interpolation between the 1992 and 2011 activity factors at the basin-level. EPA developed year- and basin-specific Subpart W EFs for 2011 forward. Year 2011 emission factors were applied to all prior years for each basin. For basins without Subpart W data available, EPA applied national average activity and emission factors (unweighted average of all Subpart W reported data).

As a result of this methodological update, CH_4 emissions estimates for non-HF workovers are on average 277 percent higher than in the previous *Inventory*. The 2021 estimate is 180 percent higher than in the previous *Inventory*. The largest increase between the estimates and the previous *Inventory* for CH_4 emissions is 698 percent

in 2017, and the smallest increase is 78 percent in 2018. The increase in CH_4 emissions is due to non-HF workovers that were vented. In the Chautauqua Platform basin (basin 355), all non-HF workovers were vented, and it had the highest CH_4 EF in 2017. The update resulted in CO_2 emissions estimates for non-HF workovers that are higher across the entire time series than the previous *Inventory* (on average 3,067 percent higher). The 2021 CO_2 emissions estimate is 116 percent higher than in the previous *Inventory*. The largest increase between estimates and the previous *Inventory* for CO_2 emissions is 7,432 percent in 1994, and the smallest increase is 78 percent in 2018. The increase in CO_2 emissions is due to non-HF workovers that were flared, particularly in the Bend Arch basin (basin 425). The Bend Arch basin has a high non-HF completion per total gas well AF and a high fraction of non-HF workovers that were flared compared to other basins over the time series.

Table 3-88: Non-HF Workovers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Workovers - vented	1,415	2,083	1,139	866	959	1,068	1,594
Non-HF Workovers - flared	NO	1,077	1	5	+	43	3
Total Emissions	**1,415**	**3,159**	**1,140**	**870**	**959**	**1,111**	**1,597**
Previous Estimate	*532*	*752*	*415*	*436*	*259*	*396*	*NA*

+ Does not exceed 0.5 MT.
NO (Not Occurring)
NA (Not Applicable)

Table 3-89: Non-HF Workovers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Non-HF Workovers - vented	87	180	61	51	2,163	199	460
Non-HF Workovers - flared	NO	174,881	269	665	34	9,591	424
Total Emissions	**87**	**175,062**	**329**	**716**	**2,197**	**9,790**	**885**
Previous Estimate	*32*	*3,701*	*185*	*294*	*476*	*4,539*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Equipment Leaks (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for onshore production equipment leaks to use basin-specific equipment-level activity factors (e.g., separators per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For this year's *Inventory*, EPA calculated equipment leak CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emissions factors for onshore production segment equipment leaks. Note, this methodological update applies only for activity factors. The previous *Inventory's* CO_2 emission factors for onshore production segment equipment leaks (by equipment type) were retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates for equipment leaks resulted in an average increase of 12 percent across the time series compared to the previous *Inventory*. Years 1990 through 2002 were minimally impacted by the updates, with an increase of 2 percent for CO_2 emissions. Years 2020 and 2021 showed larger increases of 69 and 48 percent for 2020 and 2021, respectively, which is mostly due to much higher emissions from meters and piping in the Powder River Basin.

Methane emissions for equipment leaks were impacted due to recalculations with updated data. CH_4 emission estimates were an average of 5 percent lower across the time series compared to the previous *Inventory*. The 2021 CH_4 estimate is 2 percent lower in 2021 compared to the previous *Inventory*. These CH_4 emissions changes were due to GHGRP submission revisions.

Table 3-90: Production Equipment Leaks National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Heaters	1,639	3,642	10,485	3,412	4,261	4,014	4,359
Separators	5,372	14,404	19,114	19,689	21,306	17,239	15,518
Dehydrators	1,261	1,690	794	677	589	893	683
Meters/Piping	5,400	10,527	11,199	11,775	30,564	24,424	11,022
Compressors	2,673	7,178	7,818	7,236	6,966	9,079	20,310
Total Emissions	**16,344**	**37,441**	**49,410**	**42,789**	**63,686**	**55,649**	**51,893**
Previous Estimate	*18,497*	*33,300*	*38,458*	*37,974*	*37,608*	*37,608*	*NA*

NA (Not Applicable)

Table 3-91: Production Equipment Leaks National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Heaters	12,305	18,436	79,890	16,158	18,568	17,581	18,476
Separators	41,579	80,745	121,349	126,037	129,133	109,610	94,591
Dehydrators	12,904	11,381	5,449	3,656	3,070	4,078	3,105
Meters/Piping	43,055	63,764	79,864	84,730	153,917	130,390	75,719
Compressors	30,307	61,753	71,705	64,771	60,637	73,636	193,389
Total Emissions	**140,150**	**236,079**	**358,256**	**295,352**	**365,325**	**335,295**	**385,280**
Previous Estimate	*137,647*	*262,188*	*363,367*	*298,930*	*369,466*	*343,686*	*NA*

NA (Not Applicable)

Chemical Injection Pumps (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for chemical injection pumps to use basin-specific equipment-level activity factors (e.g., pumps per well) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous *Inventory* still relied on a national-level methodology to estimate CO_2 emissions. For the current *Inventory*, EPA calculated chemical injection pump CO_2 emissions in the same manner as CH_4 emissions. EPA calculated CO_2 estimates using the basin-specific equipment-level activity factors for RY2015 through RY2022 from GHGRP, consistent with the methodology used to calculate the CH_4 activity factors, and the CO_2 emission factor. Note, this methodological update applies only for activity factors. The previous *Inventory's* chemical injection pumps CO_2 emission factor was retained and used to develop CO_2 estimates.

The update for CO_2 emission estimates resulted in an average decrease of 9 percent across the time series compared to the previous *Inventory*. There were larger decreases of 31 and 39 percent for 2020 and 2021, respectively. The recent years of the time series used basin-specific activity factors and certain basins had lower activity factors compared to the national average factors (e.g., Permian Basin, Denver Basin, San Juan, Paradox, AK Cook Inlet).

Table 3-92: Chemical Injection Pumps National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Chemical Injection Pumps	2,153	6,749	10,254	9,392	7,339	6,469	6,428
Previous Estimate	*2,275*	*7,760*	*11,053*	*10,899*	*10,635*	*10,635*	*NA*

NA (Not Applicable)

Pneumatic Controllers (Methodological Update)

In the previous *Inventory*, EPA updated the CH_4 emissions calculation methodology for pneumatic controllers to use basin-specific activity factors and emission factors by bleed type (i.e., low, high, intermittent bleed) from GHGRP data. However, the CO_2 emissions calculation methodology was not updated and instead the previous

Inventory still relied on a national-level methodology to estimate CO_2 emissions. For the current *Inventory*, EPA calculated pneumatic controller CO_2 emissions using basin-specific emissions data such that the CO_2 emissions reflect the unique CO_2 composition of the gas in a basin.

The update for pneumatic controller CO_2 emission estimates resulted in an average decrease of 44 percent across the time series compared to the previous *Inventory*. This average decrease is generally consistent for all years.

Methane emissions for pneumatic controllers were impacted due to recalculations with updated data. Methane emissions estimates are on average 0.3 percent lower across the time-series than in the previous *Inventory*. The estimate for 2021 is 2 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-93: Pneumatic Controllers National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Low Bleed Controllers	NO	1,318	2,325	2,283	2,047	1,773	2,180
High Bleed Controllers	23,058	32,794	4,378	2,898	2,373	2,418	1,726
Intermittent Bleed Controllers	15,076	41,267	56,974	57,147	48,052	44,964	37,897
Total Emissions	**38,135**	**75,378**	**63,677**	**62,328**	**52,472**	**49,155**	**41,803**
Previous Estimate	*70,028*	*129,648*	*115,235*	*115,591*	*98,144*	*91,662*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-94: Pneumatic Controllers National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Low Bleed Controllers	NO	22,656	33,220	31,099	27,238	25,247	29,877
High Bleed Controllers	355,671	480,272	86,764	52,676	42,269	41,435	30,700
Intermittent Bleed Controllers	233,661	565,070	830,140	875,168	748,219	680,708	583,144
Total Emissions	**589,332**	**1,067,997**	**950,124**	**958,943**	**817,727**	**747,391**	**643,721**
Previous Estimate	*581,039*	*1,075,712*	*956,125*	*959,080*	*814,318*	*760,534*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Storage Tanks (Recalculation with Updated Data)

Methane emissions for production condensate storage tanks are on average lower than the previous *Inventory* by less than 0.1 percent across the 1990 to 2021 time series. The 2021 estimate is 6 percent lower than in the previous *Inventory*. The production storage tanks CO_2 emissions estimates are on average 3 percent higher across the 1990 to 2021 time series than in the previous Inventory. The 2021 estimate is 25 percent higher than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-95: Storage Tanks National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	520	337	1,284	819	765	715	467
Large Tanks w/VRU	NO	27	141	464	743	597	94
Large Tanks w/o Control	16,743	6,828	15,179	3,149	5,323	4,205	3,319
Small Tanks w/Flares	NO	51	235	207	200	161	166
Small Tanks w/o Flares	92,334	31,003	43,050	61,331	47,423	35,460	33,455
Malfunctioning Separator Dump Valves	7	4	40	79	255	212	67
Total Emissions	109,605	38,250	59,929	66,049	54,708	41,351	37,567
Previous Estimate	*106,429*	*38,461*	*60,556*	*67,595*	*53,613*	*44,217*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Table 3-96: Storage Tanks National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Large Tanks w/Flares	587	421	1,476	974	1,108	1,049	575
Large Tanks w/VRU	NO	2	+	+	1	1	+
Large Tanks w/o Control	2	1	36	1	1	1	+
Small Tanks w/Flares	NO	13	86	82	41	27	20
Small Tanks w/o Flares	48	17	26	32	23	17	18
Malfunctioning Separator Dump Valves	+	+	+	+	1	+	+
Total Emissions	**637**	**455**	**1,625**	**1,089**	**1,175**	**1,094**	**613**
Previous Estimate	*628*	*456*	*1,507*	*956*	*862*	*873*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Liquids Unloading (Recalculation with Updated Data)

Liquids unloading CH_4 emissions estimates decreased by an average of 9 percent across the 1990 to 2021 time series compared with the previous *Inventory*. The 2021 estimate decreased by 17 percent compared with the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-97: Liquids Unloading National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Liquids Unloading With Plunger Lifts	0	128,295	82,501	75,081	51,457	33,916	30,384
Liquids Unloading Without Plunger Lifts	77,767	198,728	132,866	104,484	84,251	65,655	54,227
Total Emissions	**77,767**	**327,023**	**215,367**	**179,565**	**135,707**	**99,572**	**84,611**
Previous Estimate	*76,815*	*358,925*	*265,173*	*209,964*	*158,968*	*120,145*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Gas engines CH_4 emissions estimates are on average 2 percent lower across the 1990 to 2021 time series compared with the previous *Inventory*. The 2021 estimate is 4 percent lower than in the previous *Inventory*. These changes were due to revisions to Enverus data.

Table 3-98: Production Gas Engines National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Gas Engines	116,587	194,140	201,660	196,996	192,854	188,374	188,611
Previous Estimate	*115,689*	*198,005*	*207,052*	*202,060*	*197,027*	*197,027*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CO_2 emissions estimates are on average 1 percent higher across the 1993 to 2021 time series compared with the previous *Inventory*, and the 2021 estimate is 12 percent higher compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-99: Miscellaneous Production Flaring National Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Miscellaneous Flaring-Gulf Coast Basin	NO	164	135	395	251	316	206
Miscellaneous Flaring-Williston Basin	NO	+	6	3	4	7	+
Miscellaneous Flaring-Permian Basin	NO	263	690	926	808	578	231

Miscellaneous Flaring-Other Basins	NO	117	476	334	237	211	238
Total Emissions	**NO**	**544**	**1,308**	**1,659**	**1,301**	**1,112**	**676**
Previous Estimate	*NO*	*543*	*1,326*	*1,595*	*1,298*	*991*	*NA*

+ Does not exceed 0.5 kt.
NO (Not Occurring)
NA (Not Applicable)

Gathering and Boosting – Station Blowdowns (Recalculation with Updated Data)

Methane emissions estimates for gathering and boosting station blowdowns are on average 0.7 percent lower across the 1990 to 2021 time series than in the previous *Inventory*. The 2021 estimate is 17 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-100: Station Blowdowns National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Station Blowdowns	20,218	26,155	79,313	39,059	40,519	35,161	32,036
Previous Estimate	*20,517*	*26,113*	*78,548*	*38,412*	*40,468*	*42,231*	*NA*

NA (Not Applicable)

Gathering and Boosting – Pneumatic Controllers (Recalculation with Updated Data)

Gathering and boosting pneumatic controllers CH_4 emissions estimates are on average 0.1 percent higher across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 is 2 percent lower than in the previous *Inventory*, largely because of a decrease in emissions from high-bleed pneumatic devices. These changes were due to GHGRP submission revisions.

Table 3-101: Pneumatic Controllers National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
High-Bleed Pneumatic Devices	17,092	22,111	25,030	24,187	22,981	20,709	18,854
Intermittent Bleed Pneumatic Devices	78,424	101,451	173,929	184,542	171,679	156,842	145,574
Low-Bleed Pneumatic Devices	2,713	3,509	5,799	6,996	6,965	6,564	6,572
Total Emissions	**98,229**	**127,072**	**204,758**	**215,725**	**201,625**	**184,116**	**171,000**
Previous Estimate	*99,843*	*127,073*	*204,748*	*215,339*	*201,415*	*187,290*	*NA*

NA (Not Applicable)

Gathering and Boosting – Acid Gas Removal Units (Recalculation with Updated Data)

Carbon dioxide emissions estimates for acid gas removal units (AGRU) are on average 0.3 percent lower across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 decreased by 4 percent compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-102: Acid Gas Removal Units National Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
AGRU	241	311	707	1,191	1,629	2,222	2,044
Previous Estimate	*245*	*311*	*707*	*1,288*	*1,655*	*2,304*	*NA*

NA (Not Applicable)

Gathering and Boosting – Yard Piping (Recalculation with Updated Data)

Methane emissions estimates for yard piping are on average 0.6 percent higher across the 1990 to 2021 time series compared with the previous *Inventory*. The emissions estimate for 2021 is 4 percent higher than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-103: Yard Piping National Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Yard Piping	36,319	46,984	86,270	94,306	94,463	96,785	101,777
Previous Estimate	*36,773*	*46,802*	*85,996*	*94,191*	*93,253*	*93,253*	*NA*

NA (Not Applicable)

Processing

Flares (Recalculation with Updated Data)

Processing segment flare CH_4 emission estimates are on average 0.5 percent lower across the 1993 to 2021 time series than in the previous *Inventory*. The CH_4 estimate for 2021 is 7 percent lower than in the previous Inventory. The processing segment flare CO_2 emission estimates decreased by an average of 0.4 percent over the 1993 to 2021 time series, while the CO_2 estimate for 2021 decreased by 6 percent compared to the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-104: Processing Segment Flares National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	NO	NA	24,173	43,887	36,985	26,807	33,586
Previous Estimate	*NO*	*NA*	*24,148*	*43,613*	*36,928*	*28,784*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Table 3-105: Processing Segment Flares National CO_2 Emissions (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Flares	NO	3,517	5,948	9,776	8,121	6,941	8,533
Previous Estimate	*NO*	*3,517*	*5,945*	*9,859*	*8,120*	*7,381*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Transmission and Storage

Transmission Compressor Station Leaks and Venting (Methodological Update)

EPA updated the methodology to estimate national level activity data for transmission compressor stations (i.e., station and compressor counts). EPA used annual data for 1996 to 2022 from FERC and PHMSA to estimate national transmission station counts and total transmission compressor counts. FERC requires major interstate transmission compression facilities to report annual data on station counts, total compressor counts, and total transmission pipeline miles. EPA compiled annual FERC data and scaled it up to the national level using PHMSA national transmission pipeline miles for 1996 to 2022. EPA retained existing *Inventory* activity data for 1990 to 1992 and used linear interpolation to estimate national station and total compressor counts for 1993 to 1995.

Total compressor counts were apportioned to reciprocating and centrifugal compressor types using data from GHGRP's Subpart W. EPA retained existing *Inventory* activity data for 1990 to 1992 and used linear interpolation

for intermediate time series years. For more details on this update, refer to the *Transmission Station Activity* memo.

This update impacts CH_4 and CO_2 emissions from leaks (including compressor leaks), dehydrator vents, pneumatic devices, flaring, and venting at transmission compression stations. As a result of this update, CH_4 emissions estimates increased by an average of 2.6 percent across the time series and decreased by 18 percent in 2021, compared to the previous *Inventory*. Emissions estimates of CO_2 increased by an average of 2.5 percent across the time series and decreased by 16 percent in 2021, compared to the previous *Inventory*.

Table 3-106: Transmission Compressor Station National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Station Total Emissions	1,096,527	704,651	581,117	585,617	580,273	585,666	588,497
Station + Compressor Fugitive Emissions	NE	NE	118,592	120,704	120,256	125,440	128,128
Reciprocating Compressor	NE	NE	347,685	342,485	333,385	325,130	322,725
Centrifugal Compressor (wet seals)	NE	NE	50,116	51,544	52,360	53,652	50,524
Centrifugal Compressor (dry seals)	NE	NE	64,724	70,884	74,272	81,444	87,120
Dehydrator vents	1,991	1,931	2,132	2,170	2,162	2,255	2,304
Flaring	305	296	606	432	522	364	492
Pneumatic Devices	213,081	87,701	31,749	31,640	30,120	30,585	31,170
High Bleed	NE	NE	9,781	9,797	9,119	8,951	8,350
Intermittent Bleed	NE	NE	21,132	21,074	20,222	20,882	22,157
Low Bleed	NE	NE	836	769	779	753	663
Station Venting	145,241	138,843	127,165	136,920	136,332	143,132	146,659
Total Emissions	**1,457,144**	**933,422**	**742,770**	**756,779**	**749,409**	**762,002**	**769,121**
Previous Estimate	*1,459,223*	*871,649*	*809,418*	*891,620*	*911,471*	*923,868*	*NA*

NE (Not Estimated at individual source level due to lack of data)
NA (Not Applicable)

Table 3-107: Transmission Compressor Station National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Station Total Emissions	32,285	20,747	17,110	17,242	17,085	17,244	17,327
Station + Compressor Fugitive Emissions	NE	NE	3,492	3,554	3,541	3,693	3,773
Reciprocating Compressor	NE	NE	10,237	10,084	9,816	9,573	9,502
Centrifugal Compressor (wet seals)	NE	NE	1,476	1,518	1,542	1,580	1,488
Centrifugal Compressor (dry seals)	NE	NE	1,906	2,087	2,187	2,398	2,565
Dehydrator vents	59	57	63	64	64	66	68
Flaring	78,386	76,030	70,366	78,424	93,510	62,974	82,004
Pneumatic Devices Transmission	6,274	4,526	945	915	863	841	876
High Bleed	NE	NE	290	280	256	226	221
Intermittent Bleed	NE	NE	631	614	587	598	639
Low Bleed	NE	NE	23	21	20	17	16
Station Venting	4,276	4,148	4,580	4,662	4,645	4,845	4,949
Total Emissions	**121,281**	**105,508**	**93,065**	**101,307**	**116,166**	**85,970**	**105,224**
Previous Estimate	*121,473*	*98,281*	*101,654*	*118,915*	*140,933*	*102,280*	*NA*

NE (Not Estimated at individual source level due to lack of data)
NA (Not Applicable)

Underground Natural Gas Storage Well Events (Methodological Update)

EPA updated the *Inventory* with CO_2 and CH_4 estimates resulting from underground natural gas storage well events that occurred in several years across the inventory time series. Previously, EPA included emissions only from the Aliso Canyon event (occurring 2015 to 2016). This update incorporates emissions from 9 events identified as occurring at storage wells. For the update, emissions from individual events were added to the year in which they occurred.

EPA calculated CH_4 emissions using the reported leak size and applying inventory assumptions for CH_4 content. The CH_4 emissions estimates were then adjusted using a 60 percent combustion efficiency if there was evidence of combustion or ignition during the event. EPA calculated CO_2 emissions only for the events where combustion or ignition occurred, using the 60 percent combustion efficiency. The *Storage Well Events* memo presents additional information and considerations for this update.

One commenter provided feedback and it focused on the 60 percent combustion efficiency. The commenter suggested using 30 percent as the combustion efficiency instead of 60 percent based on research from Gvakharia et al., 2017, which lists 30 percent as the lowest flare efficiency.[83] The commenter noted the study used to justify the 60 percent combustion efficiency evaluated engineered flares which may not be representative of combustion during emergency events.

The newly incorporated events occurred in years 1992, 1998, 2001, 2002, 2003, 2004, 2006, 2010, and 2011. They emitted on average 7,085 metric tons of CH_4 and 27,056 metric tons CO_2.

Methane emissions estimates for underground natural gas storage wells increased 15 percent across the time series compared to previous estimates. The largest increase between the updates and the previous estimates occurs in 2004, which incorporates CH_4 emissions from the Moss Bluff event.

Updates to CO_2 emissions resulted in an increase of 1,693 percent across the time series compared to previous estimates. This increase is mostly due to additions for 2001 and 2004 estimates, resulting from Yaggy and Moss Bluff events, respectively. Combustion occurred at both of these events, resulting in the application of the 60 percent combustion efficiency.

Pipeline Venting (Recalculation with Updated Data)

Transmission pipeline venting CH_4 emission estimates are on average 0.1 percent lower across the 1990 to 2021 time series than in the previous *Inventory*. The CH_4 emissions estimate for 2021 is 4 percent lower than in the previous *Inventory*. These changes were due to GHGRP submission revisions.

Table 3-108: Pipeline Venting National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Pipeline Venting	177,951	183,159	208,438	187,266	220,544	165,703	133,761
Previous Estimate	*177,951*	*183,159*	*208,438*	*187,266*	*220,560*	*172,287*	*NA*

NA (Not Applicable)

Distribution

There were no methodological updates to the distribution segment and recalculations resulted in an average decrease in CH_4 emissions across the 1990 to 2021 time series of less than 0.1 percent and an average decrease in calculated CO_2 emissions across the 1990 to 2021 time series of less than 0.1 percent, compared to the previous *Inventory*.

[83] Gvakharia et al, 2017. Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota. *Environmental Science & Technology.* 51: 5317-5325. https://doi.org/10.1021/acs.est.6b05183.

Post-Meter

There were no methodological updates to estimate post-meter emissions and recalculations resulted in an average decrease in CH_4 emissions across the 1990 to 2021 time series of less than 0.1 percent and an average decrease in calculated CO_2 emissions across the 1990 to 2021 time series of less than 0.1 percent, compared to the previous *Inventory*.

Planned Improvements

Planned Improvements for 2025 *Inventory*

EPA updated the Enverus data and there were notable increases in the number of wells and completions identified as being hydraulically fractured compared with previous versions of the database. EPA will assess the underlying Enverus data to determine the cause of these changes.

Upcoming Data, and Additional Data that Could Inform the *Inventory*

EPA will assess new data received by EPA's Greenhouse Gas Reporting Program and Methane Challenge Program on an ongoing basis, which may be used to validate or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the *Inventory*. EPA will also continue to assess studies that include and compare both top-down and bottom-up emission estimates, which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in previous stakeholder comments.

3.8 Abandoned Oil and Gas Wells (CRT Source Categories 1B2a and 1B2b)

The term "abandoned wells", as used in the *Inventory*, encompasses various types of oil and gas wells, including orphaned wells and other non-producing wells:

- Wells with no recent production, and not plugged. Common terms (such as those used in state databases) might include: inactive, temporarily abandoned, shut-in, dormant, and idle.
- Wells with no recent production and no responsible operator. Common terms might include: orphaned, deserted, long-term idle, and abandoned.
- Wells that have been plugged to prevent migration of gas or fluids.

The U.S. population of abandoned oil and gas wells (including orphaned wells and other non-producing wells) is around 3.9 million (with around 3.0 million abandoned oil wells and 0.9 million abandoned gas wells). The methods to calculate emissions from abandoned wells involve calculating the total populations of plugged and unplugged abandoned oil and gas wells in the United States and the application of emission factors. An estimate of the number of orphaned wells within this population is not developed as part of the methodology. Wells that are plugged have much lower average emissions than wells that are unplugged (less than 1 kg CH_4 per well per year, versus over 100 kg CH_4 per well per year). Around 43 percent of the abandoned well population in the United States is plugged. This fraction has increased over the *Inventory* time series (from around 22 percent in 1990) as more wells fall under regulations and programs requiring or promoting plugging of abandoned wells.

Abandoned oil wells. Abandoned oil wells emitted 235 kt CH_4 and 5 kt CO_2 in 2022. Emissions of both gases increased by 3 percent from 1990, while the total population of abandoned oil wells increased 40 percent.

Abandoned gas wells. Abandoned gas wells emitted 68 kt CH_4 and 3 kt CO_2 in 2022. Emissions of both gases increased by 33 percent from 1990, while the total population of abandoned gas wells increased 83 percent.

Table 3-109: CH_4 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	6.4	6.6	6.6	6.6	6.6	6.6	6.6
Abandoned Gas Wells	1.4	1.6	1.8	1.8	1.9	1.9	1.9
Total	**7.8**	**8.2**	**8.4**	**8.5**	**8.5**	**8.6**	**8.5**

Note: Totals may not sum due to independent rounding.

Table 3-110: CH_4 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	228	236	237	237	237	237	235
Abandoned Gas Wells	51	58	64	65	66	69	68
Total	**279**	**294**	**301**	**302**	**303**	**306**	**303**

Note: Totals may not sum due to independent rounding.

Table 3-111: CO_2 Emissions from Abandoned Oil and Gas Wells (MMT CO_2)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	+	+	+	+	+	+	+
Abandoned Gas Wells	+	+	+	+	+	+	+
Total	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-112: CO_2 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Oil Wells	5	5	5	5	5	5	5
Abandoned Gas Wells	2	3	3	3	3	3	3
Total	**7**	**7**	**8**	**8**	**8**	**8**	**8**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses a Tier 2 method from IPCC (2019) to quantify emissions from abandoned oil and gas wells. EPA's approach is based on the number of plugged and unplugged abandoned wells in the Appalachian region and in the rest of the U.S., and emission factors for plugged and unplugged abandoned wells in Appalachia and the rest of the U.S. Methods for abandoned wells are unavailable in IPCC (2006). The details of this approach and of the data sources used are described in the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo).*

EPA developed abandoned well CH_4 emission factors using data from Kang et al. (2016) and Townsend-Small et al. (2016). Plugged and unplugged abandoned well CH_4 emission factors were developed at the national-level (using emission data from Townsend-Small et al.) and for the Appalachia region (using emission data from measurements in Pennsylvania and Ohio conducted by Kang et al. and Townsend-Small et al., respectively). The Appalachia region emissions factors were applied to abandoned wells in states in the Appalachian basin region, and the national-level emission factors were applied to abandoned wells in all other states. EPA developed abandoned well CO_2 emission factors using the CH_4 emission factors and an assumed ratio of CO_2-to-CH_4 gas content, similar to the approach used to calculate CO_2 emissions for many sources in Petroleum Systems and Natural Gas Systems. For abandoned

oil wells, EPA used the Petroleum Systems default production segment associated gas ratio of 0.020 MT CO_2/MT CH_4, which was derived through API TankCalc modeling runs. For abandoned gas wells, EPA used the Natural Gas Systems default production segment CH_4 and CO_2 gas content values (GRI/EPA 1996, GTI 2001) to develop a ratio of 0.044 MT CO_2/MT CH_4. The same respective emission factors are applied for each year of the time series.

EPA developed state-level annual counts of abandoned wells for 1990 through 2022 by summing together an annual estimate of abandoned wells in the Enverus data set (Enverus 2023), and an estimate of total abandoned wells not included the Enverus dataset (see 2018 Abandoned Wells Memo for additional information on how the value was calculated) for each state. References reviewed to develop the number of abandoned wells not included in the Enverus dataset include historical records collected by state agencies and by USGS.

The state-level abandoned well population was then split into plugged and unplugged wells by applying an assumption that all abandoned wells were unplugged in 1950 and using Enverus data to calculate the fraction of plugged abandoned wells in 2022. Linear interpolation was applied between the 1950 value and 2022 value to calculate the plugged fraction for intermediate years. See the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo)* for details.[84]

Abandoned Oil Wells

Table 3-113: Abandoned Oil Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990	2005	2018	2019	2020	2021	2022
Plugged abandoned oil wells	475,939	810,564	1,156,633	1,192,282	1,227,566	1,263,583	1,281,380
Unplugged abandoned oil wells	1,697,730	1,787,095	1,781,964	1,783,807	1,784,834	1,785,340	1,767,543
Total Abandoned Oil Wells	2,173,669	2,597,659	2,938,597	2,976,089	3,012,400	3,048,923	3,048,923
Abandoned oil wells in Appalachia	22%	20%	19%	19%	18%	18%	18%
Abandoned oil wells outside of Appalachia	78%	80%	81%	81%	82%	82%	82%
CH_4 from plugged abandoned oil wells (kt)	0.17	0.25	0.34	0.35	0.36	0.36	0.37
CH_4 from unplugged abandoned oil wells(kt)	227.6	236.1	236.5	236.9	237.0	236.8	235.0
Total CH_4 from abandoned oil wells (kt)	**227.7**	**236.4**	**236.8**	**237.2**	**237.3**	**237.2**	**235.4**
Total CO_2 from abandoned oil wells (kt)	**4.6**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**

Abandoned Gas Wells

Table 3-114: Abandoned Gas Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990	2005	2018	2019	2020	2021	2022
Plugged abandoned gas wells	110,089	210,902	348,625	359,018	372,605	389,745	395,236
Unplugged abandoned gas wells	355,620	404,960	447,374	448,504	453,988	463,119	457,628
Total Abandoned Gas Wells	465,709	615,862	795,999	807,522	826,593	852,864	852,864
Abandoned gas wells in Appalachia	28%	25%	24%	24%	24%	26%	26%

[84] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Abandoned gas wells outside of Appalachia	72%	75%	76%	76%	76%	74%	74%
CH_4 from plugged abandoned gas wells (kt)	0.06	0.11	0.17	0.17	0.19	0.21	0.21
CH_4 from unplugged abandoned gas wells (kt)	51.1	57.5	64.1	64.5	65.9	68.5	67.8
Total CH_4 from abandoned gas wells (kt)	**51.1**	**57.6**	**64.3**	**64.7**	**66.1**	**68.7**	**68.0**
Total CO_2 from abandoned gas wells (kt)	**2.2**	**2.5**	**2.8**	**2.8**	**2.9**	**3.0**	**3.0**

Uncertainty

To characterize uncertainty surrounding estimates of abandoned well emissions, EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo simulation technique). See the 2018 Abandoned Wells Memo for details of the uncertainty analysis methods. EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around total methane emissions from abandoned oil and gas wells in year 2022, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates for each population. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. EPA used measurement data from the Kang et al. (2016) and Townsend-Small et al. (2016) studies to characterize the CH_4 emission factor PDFs. For activity data inputs (e.g., total count of abandoned wells, split between plugged and unplugged), EPA assigned default uncertainty bounds of ± 10 percent based on expert judgment.

The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below in Table 3-115 provide the 95 percent confidence bound within which actual emissions from abandoned oil and gas wells are likely to fall for the year 2022, using the recommended IPCC methodology. Abandoned oil well CH_4 emissions in 2022 were estimated to be between 1.1 and 19.7 MMT CO_2 Eq., while abandoned gas well CH_4 emissions were estimated to be between 0.3 and 5.4 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series.

Table 3-115: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum and Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Oil Wells	CH_4	6.6	1.1	19.7	-83%	+204%
Abandoned Gas Wells	CH_4	1.9	0.3	5.4	-83%	+204%
Abandoned Oil Wells	CO_2	0.005	0.001	0.014	-83%	+204%
Abandoned Gas Wells	CO_2	0.003	0.0005	0.008	-83%	+204%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo simulation analysis conducted for total abandoned oil and gas well CH_4 emissions in year 2022.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in the table.

QA/QC and Verification Discussion

The emission estimates in the *Inventory* are continually reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. In order to ensure the quality of emission estimates for abandoned wells, general (IPCC Tier 1) quality assurance/quality control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Additionally, EPA reviewed the current Enverus dataset and compared it with results from the previous dataset to identify outliers and instances of significant changes to abandoned oil and gas well counts.

EPA performs a thorough review of information associated with new studies to assess whether the assumptions in the *Inventory* are consistent with industry practices and whether new data is available that could be considered for updates to the estimates. As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held a stakeholder webinar on greenhouse gas data for oil and gas in October of 2023.

Recalculations Discussion

EPA updated the *Inventory* with revised abandoned oil and gas well counts developed from Enverus data (Enverus 2023). Compared to the previous *Inventory*, annual abandoned oil well counts increased by an average of 2 percent across the time series and increased by 4 percent in 2021. Annual abandoned gas well counts increased by 2 percent across the time series and 7 percent in 2021. Similarly, both plugged wells and unplugged wells increased by 2 percent across the time series. As a result of this update, calculated abandoned oil well CH_4 and CO_2 emissions increased by an average of 2 percent each year across the time series and increased by 3 percent in 2021, compared to the previous *Inventory*. Abandoned gas well CH_4 and CO_2 emissions increased by an average of 1 percent across the time series and increased by 8 percent in 2021, compared to the previous *Inventory*.

Planned Improvements

EPA will continue to assess new data and stakeholder feedback on considerations (such as potential use of emission factor data from regions not included in the measurement studies on which current emission factors are based) to improve the abandoned well count estimates and emission factors. In future Inventories, EPA will assess data that become available from Department of Interior and Department of Energy orphan well plugging programs.

3.9 International Bunker Fuels (CRT Source Category 1: Memo Items)

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the Paris Agreement and the UNFCCC, are not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental

Negotiating Committee in establishing the Framework Convention on Climate Change.[85] These decisions are reflected in the IPCC methodological guidance, including IPCC (2006), in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC 2006).[86]

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[87] Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O for marine transport modes, and CO_2 and N_2O for aviation transport modes. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The *2006 IPCC Guidelines* distinguish between three different modes of air traffic: civil aviation, military aviation, and general aviation. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The *2006 IPCC Guidelines* further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the *2006 IPCC Guidelines*, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil and military aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[88]

Emissions of CO_2 from aircraft are essentially a function of fuel consumption. Nitrous oxide emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Recent data suggest that little or no CH_4 is emitted by modern engines (Anderson et al. 2011), and as a result, CH_4 emissions from this category are reported as zero. In jet engines, N_2O is primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase.

International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., U.S. Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2022 from the combustion of international bunker fuels from both aviation and marine activities were 99.1 MMT CO_2 Eq., or 5.2 percent below emissions in 1990 (see Table 3-116 and Table 3-117). Emissions from international flights and international shipping voyages departing from the United States have increased by 74.4 percent and decreased by 51.7 percent, respectively, since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 (from marine transport modes) and N_2O were also emitted.

[85] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c).

[86] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[87] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

[88] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

Table 3-116: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990	2005	2018	2019	2020	2021	2022
CO_2	**103.6**	**113.3**	**124.3**	**113.6**	**69.6**	**80.2**	**98.2**
Aviation	38.2	60.2	83.0	78.3	39.8	50.8	66.6
Commercial	*30.0*	*55.6*	*79.8*	*75.1*	*36.7*	*47.6*	*63.5*
Military	*8.2*	*4.6*	*3.2*	*3.2*	*3.1*	*3.2*	*3.1*
Marine	65.4	53.1	41.3	35.4	29.9	29.4	31.6
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.8**	**0.9**	**1.0**	**0.9**	**0.5**	**0.6**	**0.8**
Aviation	0.3	0.5	0.7	0.7	0.3	0.4	0.6
Marine	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Total	**104.6**	**114.3**	**125.3**	**114.6**	**70.3**	**80.9**	**99.1**

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-117: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990	2005	2018	2019	2020	2021	2022
CO_2	**103,634**	**113,328**	**124,279**	**113,632**	**69,638**	**80,180**	**98,241**
Aviation	38,205	60,221	82,953	78,280	39,781	50,812	66,646
Marine	65,429	53,107	41,325	35,351	29,857	29,369	31,595
CH_4	**7**	**5**	**4**	**4**	**3**	**3**	**3**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	7	5	4	4	3	3	3
N_2O	**3**	**3**	**4**	**3**	**2**	**2**	**3**
Aviation	1	2	3	2	1	2	2
Marine	2	1	1	1	1	1	1

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Methodology and Time-Series Consistency

Emissions of CO_2 were for the most part estimated by applying carbon content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under Section 3.1. Carbon content and fraction oxidized factors for jet fuel (except for commercial aviation as per below), distillate fuel oil, and residual fuel oil are the same as used for CO_2 from Fossil Fuel Combustion and are presented in Annex 2.1, Annex 2.2, and Annex 3.8 of this *Inventory*. Density conversions were taken from ASTM (1989) and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2024) and USAF (1998), and heat content for jet fuel was taken from EIA (2024). See below for details on how emission estimates for commercial aviation were determined.

A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.8 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), which is also referenced in the *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following value, in units of grams of pollutant per kilogram of fuel consumed (g/kg), was employed: 0.1 for N_2O (IPCC 2006). For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.315 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on domestic and international aircraft fuel consumption were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 1990 and 2000 through 2022 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines* (IPCC 2006).

International aviation CO_2 estimates for 1990 and 2000 through 2022 were obtained directly from FAA's AEDT model (FAA 2024). The radar-informed method that was used to estimate CO_2 emissions for commercial aircraft for 1990 and 2000 through 2022 was not possible for 1991 through 1999 because the radar dataset was not available for years prior to 2000. FAA developed Official Airline Guide (OAG) schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000, and 2010. Because fuel consumption and CO_2 emission estimates for years 1991 through 1999 are unavailable, consumption estimates for these years were calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on 2000 through 2005 data. See Annex 3.3 for more information on the methodology for estimating emissions from commercial aircraft jet fuel consumption.

Data on U.S. Department of Defense (DoD) aviation bunker fuels and total jet fuel consumed by the U.S. military was supplied by the Office of the Under Secretary of Defense (Installations and Environment), DoD. Estimates of the percentage of each Service's total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Military aviation bunker fuel emissions were estimated using military fuel and operations data synthesized from unpublished data from DoD's Defense Logistics Agency Energy (DLA Energy 2023). Together, the data allow the quantity of fuel used in military international operations to be estimated. Densities for each jet fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 3-118. See Annex 3.8 for additional discussion of military data.

Table 3-118: Aviation Jet Fuel Consumption for International Transport (TBtu)

Nationality	1990	2005	2018	2019	2020	2021	2022
U.S. and Foreign Carriers	426	791	1,104	1,068	521	677	902
U.S. Military	116	64	44	44	43	44	44
Total	**542**	**854**	**1,148**	**1,112**	**564**	**721**	**946**

Note: Totals may not sum due to independent rounding.

In order to quantify the civilian international component of marine bunker fuels, activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were collected for individual shipping agents on a monthly basis by the U.S. Customs and Border Protection. This information was then reported in unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 1991 through 2022) for 1990 through 2001, 2007 through 2022, and the Department of Homeland Security's Bunker Report for 2003 through 2006 (DHS 2008). Fuel consumption data for 2002 was interpolated due to inconsistencies in reported fuel consumption data. Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DLA Energy (2023). The total amount of fuel provided to naval vessels was reduced by 21 percent to account for fuel used while the vessels were not underway (i.e., in port). Data on the percentage of steaming hours underway versus not underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 3-119.

Table 3-119: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	2005	2018	2019	2020	2021	2022
Residual Fuel Oil	4,781	3,881	2,790	2,246	1,964	1,953	2,172
Distillate Diesel Fuel & Other	617	444	684	702	461	437	435
U.S. Military Naval Fuels	522	471	285	281	296	285	263
Total	**5,920**	**4,796**	**3,759**	**3,229**	**2,721**	**2,674**	**2,870**

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[89] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Uncertainties exist with regard to the total fuel used by military aircraft and ships. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the DoD Components (e.g., Army, Department of Navy and Air Force) from the Defense Logistics Agency Energy. These data may not include fuel used in aircraft and ships as a result of a Service procuring fuel from, selling fuel to, trading fuel with, or giving fuel to other ships, aircraft, governments, or other entities.

Additionally, there are uncertainties in historical aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty associated with ground fuel estimates for 1997 through 2022, including estimates for the quantity of jet fuel allocated to ground transportation. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are also uncertainties in fuel end-uses by fuel type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. The data were adjusted for trends in fuel use based on a closely correlating, but not matching, data set. All assumptions used to develop the estimate were based on process knowledge, DoD data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated but is believed to be small. The uncertainties associated with future military bunker fuel emission estimates could be reduced through revalidation of assumptions based on data regarding current equipment and operational tempo, however, it is doubtful data with more fidelity exist at this time.

[89] See uncertainty discussions under section 3.1 CO_2 from Fossil Fuel Combustion.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *2006 IPCC Guidelines* (IPCC 2006) is to use data by specific aircraft type, number of individual flights and, ideally, movement data to better differentiate between domestic and international aviation and to facilitate estimating the effects of changes in technologies. The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[90]

There is also concern regarding the reliability of the existing DOC (1991 through 2022) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

QA/QC and Verification

In order to ensure the quality of the emission estimates from international bunker fuels, General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8 The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O emissions from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

EPA will evaluate data availability to update the sources for densities, energy contents, and emission factors applied to estimate emissions from aviation and marine fuels. Many are from sources from the late 1990s, such as IPCC/UNEP/OECD/IEA (1997). Potential sources with more recent data include the International Maritime Organization (IMO) greenhouse gas emission inventory, International Air Transport Association (IATA)/ICAO greenhouse gas reporting system (CORSIA), and the EPA Greenhouse Gas Reporting Program (GHGRP) Technical Support Document for Petroleum Products. Specifically, EPA will evaluate data availability to support updating the heat contents and carbon contents of jet fuel with input from EIA.

A longer-term effort is underway to consider the feasibility of including data from a broader range of domestic and international sources for bunker fuels. Potential sources include the IMO greenhouse gas emission inventory, data from the U.S. Coast Guard on vehicle operation currently used in criteria pollutant modeling, data from the International Energy Agency (IEA), relevant updated FAA models to improve aviation bunker fuel estimates, and researching newly available marine bunker data.

[90] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends website, and reported under the Mobile Combustion section. It should be noted that these estimates are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates reported under the Mobile Combustion section overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights, but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes.

3.10 Biomass and Biofuels Consumption (CRT Source Category 1A)

The combustion of biomass—such as wood, charcoal, the biogenic portions of MSW, and wood waste and biofuels such as ethanol, biogas, and biodiesel—generates CO_2 in addition to CH_4 and N_2O already covered in this chapter. In line with the reporting requirements for inventories submitted under the Paris Agreement and the UNFCCC, CO_2 emissions from biomass and biofuel combustion have been estimated separately from fossil fuel CO_2 emissions and are not directly included in the energy sector contributions to U.S. totals. In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands. For a more complete description of this methodological approach, see the Land Use, Land-Use Change, and Forestry chapter (Chapter 6), which accounts for the contribution of any resulting CO_2 emissions to U.S. totals within the Land Use, Land-Use Change, and Forestry sector's approach.

Therefore, CO_2 emissions from biomass and biofuel consumption are not included specifically in summing energy sector totals. However, they are presented here for informational purposes and to provide detail on biomass and biofuels consumption.

In 2022, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electric power sectors were approximately 195.3 MMT CO_2 Eq. (195,338 kt) (see Table 3-120 and Table 3-121). As the largest consumer of woody biomass, the industrial sector was responsible for 62.9 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 22.3 percent of the total, while the electric power and commercial sectors accounted for the remainder.

Table 3-120: CO_2 Emissions from Wood Consumption by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	135.3	136.3	134.4	132.1	127.3	128.2	122.8
Residential	59.8	44.3	54.1	56.3	35.6	35.5	43.6
Commercial	6.8	7.2	8.7	8.7	8.6	8.5	8.6
Electric Power	13.3	19.1	22.8	20.7	19.1	20.3	20.4
Total	**215.2**	**206.9**	**220.0**	**217.7**	**190.6**	**192.5**	**195.3**

Note: Totals may not sum due to independent rounding.

Table 3-121: CO_2 Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	135,348	136,269	134,417	132,069	127,301	128,209	122,824
Residential	59,808	44,340	54,122	56,251	35,585	35,484	43,565
Commercial	6,779	7,218	8,669	8,693	8,554	8,528	8,563
Electric Power	13,252	19,074	22,795	20,677	19,115	20,288	20,385
Total	**215,186**	**206,901**	**220,003**	**217,690**	**190,554**	**192,509**	**195,338**

Note: Totals may not sum due to independent rounding.

Carbon dioxide emissions from combustion of the biogenic components of MSW by the electric power sector were an estimated 14.9 MMT CO_2 (14,864 kt) in 2022. Emissions across the time series are shown in Table 3-122 and Table 3-123. As discussed in Section 3.3, MSW is combusted to produce electricity and the CO_2 emissions from the fossil portion of the MSW (e.g., plastics, textiles, etc.) are included in the energy sector FFC estimates. The MSW also includes biogenic components (e.g., food waste, yard trimmings, natural fibers) and the CO_2 emissions associated with that biogenic portion is included here.

Table 3-122: CO_2 Emissions from Biogenic Components of MSW (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Electric Power	18.5	14.7	16.1	15.7	15.6	15.3	14.9

Table 3-123: CO_2 Emissions from Biogenic Components of MSW (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Electric Power	18,534	14,722	16,115	15,709	15,614	15,329	14,864

The transportation sector is responsible for most of the fuel ethanol consumption in the United States. Ethanol used for fuel is currently produced primarily from corn grown in the Midwest, but it can be produced from a variety of biomass feedstocks. Most ethanol for transportation use is blended with gasoline to create a 90 percent gasoline, 10 percent by volume ethanol blend known as E-10 or gasohol.

In 2022, the United States transportation sector consumed an estimated 1,094.9 trillion Btu of ethanol (94 percent of total), and as a result, produced approximately 75.0 MMT CO_2 Eq. (74,953 kt) (see Table 3-124 and Table 3-125) of CO_2 emissions. Smaller quantities of ethanol were also used in the industrial and commercial sectors. Ethanol fuel production and consumption has grown significantly since 1990 due to the favorable economics of blending ethanol into gasoline and federal policies that have encouraged use of renewable fuels.

Table 3-124: CO_2 Emissions from Ethanol Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	4.1	21.6	78.6	78.7	68.1	75.4	75.0
Industrial	0.1	1.2	1.4	1.6	1.6	1.5	1.9
Commercial	0.1	0.2	1.9	2.2	2.2	2.1	2.7
Total	**4.2**	**22.9**	**81.9**	**82.6**	**71.8**	**79.1**	**79.6**

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.
Note: Totals may not sum due to independent rounding.

Table 3-125: CO_2 Emissions from Ethanol Consumption (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	4,059	21,616	78,603	78,739	68,085	75,417	74,953
Industrial	105	1,176	1,404	1,610	1,582	1,509	1,919
Commercial	63	151	1,910	2,229	2,182	2,139	2,721
Total	**4,227**	**22,943**	**81,917**	**82,578**	**71,848**	**79,064**	**79,593**

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.
Note: Totals may not sum due to independent rounding.

The transportation sector is assumed to be responsible for all of the biodiesel consumption in the United States (EIA 2024a). Biodiesel is currently produced primarily from soybean oil, but it can be produced from a variety of biomass feedstocks including waste oils, fats, and greases. Biodiesel for transportation use appears in low-level blends (less than 5 percent) with diesel fuel, high-level blends (between 6 and 20 percent) with diesel fuel, and 100 percent biodiesel (EIA 2024b).

In 2022, the United States consumed an estimated 211.6 trillion Btu of biodiesel, and as a result, produced approximately 15.6 MMT CO_2 Eq. (15,622 kt) (see Table 3-126 and Table 3-127) of CO_2 emissions. Biodiesel production and consumption has grown significantly since 2001 due to the favorable economics of blending biodiesel into diesel and federal policies that have encouraged use of renewable fuels (EIA 2024b). There was no measured biodiesel consumption prior to 2001 EIA (2024a).

Table 3-126: CO_2 Emissions from Biodiesel Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	NO	0.9	17.9	17.1	17.7	16.1	15.6

NO (Not Occurring)

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.

Table 3-127: CO_2 Emissions from Biodiesel Consumption (kt)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation[a]	NO	856	17,936	17,080	17,678	16,112	15,622

NO (Not Occurring)

[a] See Annex 3.2, Table A-74 for additional information on transportation consumption of these fuels.

Methodology and Time-Series Consistency

Woody biomass emissions were estimated by applying two gross heat contents from EIA (Lindstrom 2006) to U.S. consumption data (EIA 2024a) (see Table 3-129), provided in energy units for the industrial, residential, commercial, and electric power sectors. One heat content (16.95 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.43 MMBtu/MT wood and wood waste) was applied to the consumption data for the other sectors. An EIA emission factor of 0.434 MT C/MT wood (Lindstrom 2006) was then applied to the resulting quantities of woody biomass to obtain CO_2 emission estimates. The woody biomass is assumed to contain black liquor and other wood wastes, have a moisture content of 12 percent, and undergo complete combustion to be converted into CO_2.

Data for total waste incinerated, excluding tires, from 1990 to 2022 was derived following the methodology described in Section 3.3. Biogenic CO_2 emissions associated with MSW combustion were obtained from EPA's GHGRP FLIGHT data for MSW combustion sources (EPA 2023). Dividing biogenic CO_2 emissions from GHGRP FLIGHT data for MSW combustors by estimated MSW tonnage combusted yielded an annual biogenic CO_2 emission factor. This approach follows the same approach used to develop the fossil CO_2 emissions from MSW combustion as discussed in Section 3.3. As this data was only available following 2011, all years prior use an average of the emission factors from 2011 through 2015.

Biogenic CO_2 emissions from MSW combustion were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated biogenic CO_2 emission factors are shown in Table 3-128.

Table 3-128: Calculated Biogenic CO_2 Content per Ton Waste (kg CO_2/Short Ton Combusted)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
CO_2 Emission Factors	556	556	553	558	566	550	564

The amount of ethanol allocated across the transportation, industrial, and commercial sectors was based on the sector allocations of ethanol-blended motor gasoline. The sector allocations of ethanol-blended motor gasoline were determined using a bottom-up analysis conducted by EPA, as described in the Methodology section of Fossil Fuel Combustion. Total U.S. ethanol consumption from EIA (2024a) was allocated to individual sectors using the same sector allocations as ethanol-blended motor gasoline. The emissions from ethanol consumption were calculated by applying an emission factor of 18.67 MMT C/Qbtu (EPA 2010) to adjusted ethanol consumption estimates (see Table 3-130). The emissions from biodiesel consumption were calculated by applying an emission

factor of 20.1 MMT C/Qbtu (EPA 2010) to U.S. biodiesel consumption estimates that were provided in energy units (EIA 2024a) (see Table 3-131).[91]

Table 3-129: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Industrial	1,441.9	1,451.7	1,432.0	1,407.0	1,356.2	1,365.9	1,308.5
Residential	580.0	430.0	524.9	545.5	345.1	344.1	422.5
Commercial	65.7	70.0	84.1	84.3	83.0	82.7	83.0
Electric Power	128.5	185.0	221.1	200.5	185.4	196.7	197.7
Total	**2,216.2**	**2,136.7**	**2,262.0**	**2,237.3**	**1,969.6**	**1,989.4**	**2,011.7**

Note: Totals may not sum due to independent rounding.

Table 3-130: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	59.3	315.8	1,148.2	1,150.2	994.6	1,101.7	1,094.9
Industrial	1.5	17.2	20.5	23.5	23.1	22.0	28.0
Commercial	0.9	2.2	27.9	32.6	31.9	31.2	39.7
Total	**61.7**	**335.1**	**1,196.6**	**1,206.3**	**1,049.5**	**1,155.0**	**1,162.7**

Note: Totals may not sum due to independent rounding.

Table 3-131: Biodiesel Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2018	2019	2020	2021	2022
Transportation	NO	11.6	242.9	231.3	239.4	218.2	211.6

NO (Not Occurring)

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

It is assumed that the combustion efficiency for biomass is 100 percent, which is believed to be an overestimate of the efficiency of biomass combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates for CO_2. Additionally, the heat content applied to the consumption of woody biomass in the residential, commercial, and electric power sectors is unlikely to be a completely accurate representation of the heat content for all the different types of woody biomass consumed within these sectors. Emission estimates from ethanol and biodiesel production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Recalculations Discussion

EIA (2024a) updated 2020 and 2021 wood energy consumed by the residential sector due to new underlying data collected by the Residential Energy Consumption Survey (RECS), which collects data about once every 5 years and uses Annual Energy Outlook growth rates to estimate data for other years. This caused CO_2 emissions from residential wood consumption to decrease by 9.9 MMT CO_2 Eq. (4.9 percent) in 2020 and 12.3 MMT CO_2 Eq. (6.0 percent) in 2021 compared to estimates in the previous *Inventory* for these years.

[91] CO_2 emissions from biodiesel do not include emissions associated with the carbon in the fuel that is from the methanol used in the process. Emissions from methanol use and combustion are assumed to be accounted for under Non-Energy Use of Fuels. See Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Planned Improvements

Future research will investigate the availability of data on woody biomass heat contents and carbon emission factors to see if there are newer, improved data sources available for these factors.

Currently, emission estimates from biomass and biomass-based fuels included in this *Inventory* are limited to woody biomass, biogenic components of MSW, ethanol, and biodiesel. Additional forms of biomass-based fuel consumption include biogas, and other renewable diesel fuels. EPA will investigate additional forms of biomass-based fuel consumption, research the availability of relevant emissions factors, and integrate these into the *Inventory* as feasible. EPA will examine EIA data on biogas and other renewable diesel fuels to see if these fuel types can be included in future Inventories. EIA (2024a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas. Distillate fuel statistics are adjusted in this *Inventory* to remove other renewable diesel fuels as well as biodiesel. Additionally, options for including "Other Renewable Fuels," as defined by EIA, will be evaluated.

The availability of facility-level combustion emissions through EPA's GHGRP will be examined to help better characterize the industrial sector's energy consumption in the United States and further classify woody biomass consumption by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, although for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the *Inventory* to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under Paris Agreement and UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under EPA's GHGRP may also include industrial process emissions.[92]

In line with the Paris Agreement and UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from biomass combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this *Inventory*. Additionally, analyses will focus on aligning reported facility-level fuel types and IPCC fuel types per the national energy statistics, ensuring CO_2 emissions from biomass are separated in the facility-level reported data, and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[93]

3.11 Energy Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, energy-related activities are also sources of greenhouse gas precursors. The reporting requirements of the Paris Agreement and the UNFCCC[94] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse

[92] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

[93] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[94] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from energy-related activities from 1990 to 2022 are reported in Table 3-132.

Table 3-132: NO_x, CO, NMVOC, and SO_2 Emissions from Energy-Related Activities (kt)

Gas/Activity	1990	2005	2018	2019	2020	2021	2022
NO_x	**21,804**	**18,196**	**6,812**	**6,503**	**5,630**	**5,570**	**5,225**
Fossil Fuel Combustion	21,678	18,188	6,804	6,496	5,624	5,563	5,218
Transportation[a]	*12,132*	*12,628*	*4,486*	*4,322*	*3,618*	*3,546*	*3,228*
Industrial	*2,475*	*1,486*	*820*	*800*	*751*	*721*	*721*
Electric Power Sector	*6,045*	*3,440*	*1,025*	*898*	*762*	*807*	*781*
Commercial	*451*	*288*	*186*	*187*	*193*	*189*	*188*
Residential	*575*	*346*	*288*	*290*	*300*	*300*	*300*
Petroleum and Natural Gas Systems	127	8	7	7	7	6	6
International Bunker Fuels	1,953	1,699	1,456	1,280	977	1,008	1,132
CO	**124,584**	**63,891**	**30,237**	**29,854**	**27,897**	**28,283**	**27,607**
Fossil Fuel Combustion	124,353	63,686	30,050	29,660	27,703	28,098	27,426
Transportation[a]	*119,478*	*59,540*	*26,024*	*25,621*	*23,546*	*23,912*	*23,235*
Residential	*3,620*	*2,393*	*2,751*	*2,860*	*2,968*	*2,950*	*2,950*
Industrial	*705*	*976*	*620*	*600*	*670*	*658*	*655*
Electric Power Sector	*329*	*582*	*505*	*428*	*362*	*423*	*428*
Commercial	*220*	*195*	*151*	*151*	*157*	*154*	*158*
Petroleum and Natural Gas Systems	232	205	186	194	194	185	181
International Bunker Fuels	102	131	158	150	83	101	128
NMVOCs	**12,269**	**8,081**	**5,050**	**4,987**	**4,822**	**5,167**	**5,045**
Fossil Fuel Combustion	11,793	6,079	2,632	2,593	2,391	2,454	2,329
Transportation[a]	*10,932*	*5,608*	*2,127*	*2,072*	*1,846*	*1,912*	*1,786*
Residential	*693*	*322*	*382*	*397*	*431*	*429*	*429*
Commercial	*9*	*18*	*14*	*14*	*14*	*14*	*14*
Industrial	*117*	*87*	*80*	*81*	*74*	*73*	*74*
Electric Power Sector	*43*	*44*	*30*	*29*	*26*	*27*	*27*
Petroleum and Natural Gas Systems	476	2,002	2,418	2,394	2,431	2,713	2,716
International Bunker Fuels	57	54	50	45	32	34	40
SO_2	**22,638**	**13,331**	**1,827**	**1,509**	**1,288**	**1,423**	**1,327**
Fossil Fuel Combustion	21,482	13,235	1,770	1,447	1,138	1,272	1,176
Electric Power Sector	*14,432*	*9,436*	*1,189*	*921*	*758*	*898*	*819*
Industrial	*2,886*	*1,378*	*259*	*234*	*172*	*168*	*159*
Transportation[a]	*793*	*724*	*45*	*40*	*23*	*24*	*25*
Commercial	*485*	*318*	*18*	*19*	*13*	*14*	*13*
Residential	*2,886*	*1,378*	*259*	*234*	*172*	*168*	*159*
Petroleum and Natural Gas Systems	156	96	56	61	150	151	151
International Bunker Fuels	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

[a] The scope of the NEI for aircraft related precursor emissions included under the transportation is different from the Paris Agreement and UNFCCC reporting scope. The NEI precursor estimate methodology does not exclude emissions that could be considered international bunkers given local impacts from these emissions. The precursor estimates are based on modeled using FAA- and state-supplied landing and take-off data for all aircraft types (including ground support equipment and auxiliary engines) used for public, private, and military purposes.

Note: Totals may not sum due to independent rounding.

Source: (EPA 2023a). Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2022 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 3-132, NEI reported emissions of CO, NO_x, NMVOCs, and SO_2 were recategorized from NEI Emissions Inventory System (EIS) sectors to source categories more

closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on discussions between the EPA *Inventory* and NEI staff (see crosswalk documented in Annex 6.3).[95] EIS sectors mapped to the energy sector categories in this report include: fuel combustion for electric utilities, industrial, and other; petroleum and related industries; highway vehicles; off-highway; and other mobile sources (e.g., commercial marine vessels and rail). As described in the NEI Technical Support Documentation (TSD) (EPA 2023b), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends website (EPA 2023a; EPA 2023b). No quantitative estimates of uncertainty were calculated for this source category.

[95] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRTs), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

4. Industrial Processes and Product Use

Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1 and Figure 4-2. Greenhouse gas emissions from industrial processes can occur in two different ways. First, they may be generated and emitted as the byproducts of various non-energy-related industrial activities. Second, they may be emitted due to their use in manufacturing processes or by end-consumers. Combustion-related energy use emissions from industry are reported in Chapter 3, Energy.

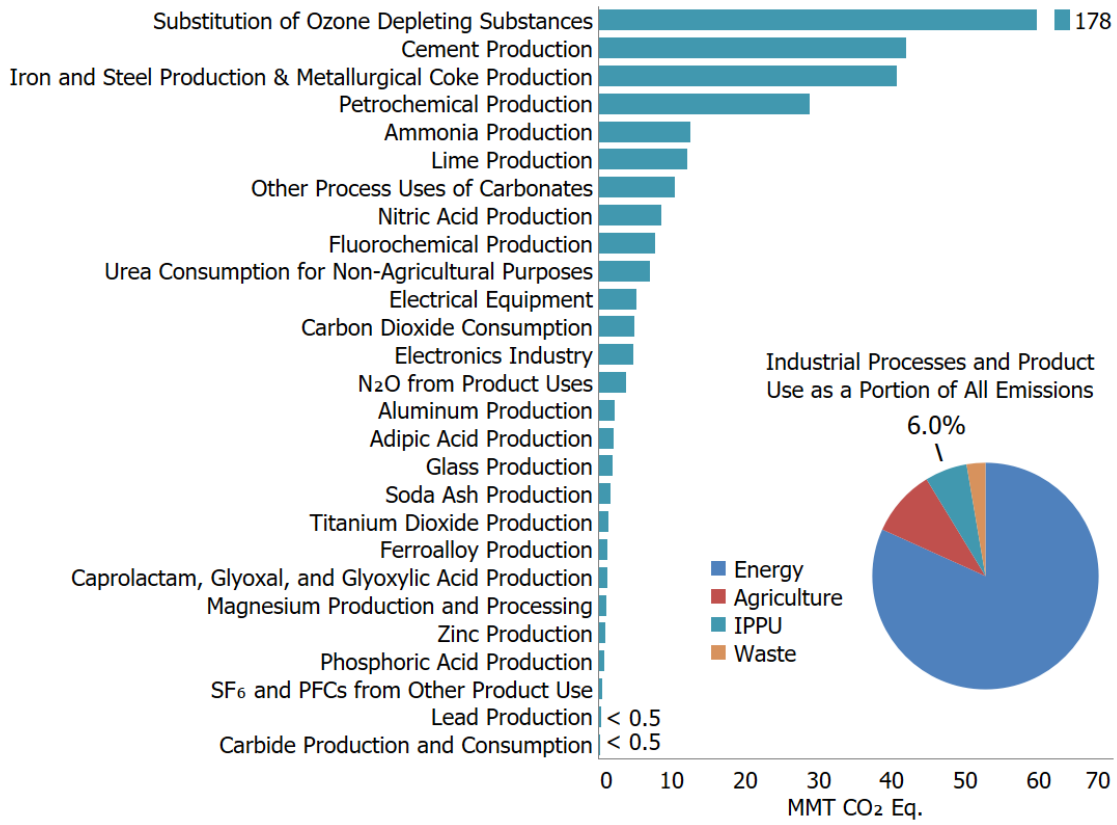
In the case of byproduct emissions, the emissions are generated by an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases (e.g., HFC-23). The greenhouse gas byproduct generating processes included in this chapter include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, ceramics production, non-metallurgical magnesia production, and soda ash consumption not associated with glass manufacturing), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, other fluorochemical production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption.

Greenhouse gases that are used in manufacturing processes or by end-consumers include man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The present contribution of HFCs, PFCs, SF_6, and NF_3 gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to persist in the atmosphere long after they were first released. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Use of HFCs continues since they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer; however, production and consumption of HFCs are being phased down under the Kigali Amendment to the Montreal Protocol and in the United States under the American Innovation and Manufacturing Act. Hydrofluorocarbons, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States, such as the electronics industry, electric power transmission and distribution, PFCs and SF_6 for other product use, and magnesium metal production and processing. Carbon dioxide is also consumed and emitted through various end-use applications. In addition, nitrous oxide is used in and emitted by the electronics industry and anesthetic and aerosol applications.

In 2022, IPPU generated emissions of 383.2 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 6.0 percent of total U.S. greenhouse gas emissions.[1] Carbon dioxide emissions from all industrial processes were 168.9 MMT CO_2 Eq. (168,937 kt CO_2) in 2022, or 3.3 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.04 MMT CO_2 Eq. (1 kt CH_4) in 2022, which was 0.01 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 16.1 MMT CO_2 Eq. (61 kt N_2O) in 2022, or 4.1 percent of total U.S. N_2O emissions. In 2022 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 198.1 MMT CO_2 Eq. Total emissions from IPPU in 2022 were 3.9 percent more than 1990 emissions. Total emissions from IPPU remained relatively constant between 2021 and 2022, increasing by 0.4 percent due to offsetting trends within the sector. More information on emissions of greenhouse gas precursors emissions that also result from IPPU are presented in Section 4.27 of this chapter.

The largest source of IPPU-related emissions is the substitution of ozone depleting substances, which accounted for 46.5 percent of sector emissions in 2022. These emissions have increased by 79.1 percent since 2005, and 3.2 percent between 2021 and 2022. Cement production was the second largest source of IPPU emissions in 2022, accounting for 10.9 percent of IPPU emissions in 2022. Iron and steel production and metallurgical coke production was the third largest source of IPPU emissions, accounting for 10.6 percent of the sector total in 2022.

Figure 4-1: Industrial Processes and Product Use Sector Greenhouse Gas Sources



The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources, as shown in Figure 4-2. Emissions resulting from most types of metal production have declined significantly since 1990, largely due to production shifting to other countries, but also due to transitions to less-emissive methods of

[1] Emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories.

production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Carbon dioxide and CH_4 emissions from some chemical production sources (e.g., petrochemical production, urea consumption for non-agricultural purposes) have increased since 1990, while emissions from other chemical production sources (e.g., ammonia production, phosphoric acid production) have decreased. Emissions from mineral sources have either increased (e.g., cement production) or not changed significantly (e.g., lime production) since 1990 and largely follow economic cycles. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990 and are the largest source of IPPU emissions (46.5 percent in 2022), while the emissions of HFCs, PFCs, SF_6, and NF_3 from other sources have generally declined. Nitrous oxide emissions from the production of nitric acid have decreased. Some emission sources (e.g., adipic acid) exhibit varied interannual trends. Trends are explained further within each emission source category throughout the chapter.

Figure 4-2: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

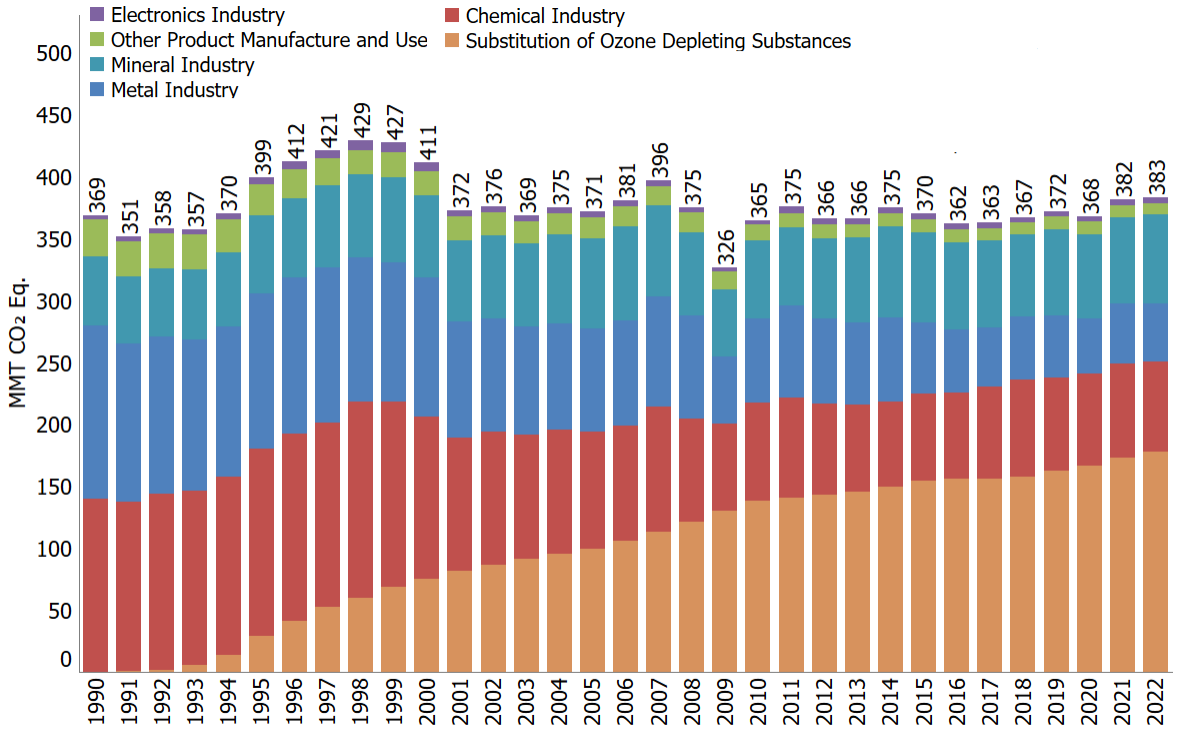


Table 4-1 summarizes emissions for the IPPU chapter in MMT CO_2 Eq. using IPCC *Fifth Assessment Report* (AR5) GWP values, following the requirements of the current United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).[2] Unweighted gas emissions in kt are also provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the Common Reporting Tables (CRTs), corresponding generally to: mineral industry, chemical industry, metal industry, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

Each year, some emission and sink estimates in the IPPU sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to

[2] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

ensure that the trend is accurate. Key updates to this year's *Inventory* include the addition of new categories previously not estimated: CO_2 emissions from ceramics production and non-metallurgical magnesia within other process use of carbonates category; fluorinated gases from production of fluorochemicals other than HCFC-22 within the fluorochemical production category; and SF_6 and PFCs from additional product uses within the other product manufacture and use category. In addition, there were changes to the petrochemical production methodology to calculate emissions from methanol production; updates to emission estimates from urea consumption for non-agricultural purposes driven by revisions to quantities of urea applied, urea imports, and urea exports; and revisions to the method for estimating SF_6 emissions from electrical equipment for estimating using CARB data from electrical equipment in California. Together, these methodological and data updates increased IPPU sector greenhouse gas emissions by an average 20.4 MMT CO_2 Eq. (7.2 percent) across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213.7**	**195.9**	**164.4**	**168.2**	**160.7**	**168.8**	**168.9**
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7
Iron and Steel Production	*99.1*	*66.2*	*41.6*	*40.1*	*35.4*	*38.6*	*37.7*
Metallurgical Coke Production	*5.6*	*3.9*	*1.3*	*3.0*	*2.3*	*3.2*	*3.0*
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
CH_4	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**
Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**29.6**	**22.2**	**23.1**	**18.7**	**20.8**	**19.7**	**16.1**
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
N_2O from Product Uses	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**
Substitution of Ozone Depleting Substances[a]	0.3	99.5	157.9	162.1	166.2	172.6	178.1
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	+	+
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0.0	+	+	+	+
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8
SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Total[b]	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

[b] Total does not include other fluorinated gases, such as HFEs and PFPEs, which are reported separately in Section 4.24.

Note: Totals may not sum due to independent rounding. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in *Inventory* totals and are included for informational purposes only in Section 4.24. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213,682**	**195,933**	**164,404**	**168,175**	**160,701**	**168,838**	**168,937**
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884
Iron and Steel Production & Metallurgical Coke Production	104,740	70,082	42,863	43,095	37,724	41,873	40,672
Iron and Steel Production	*99,132*	*66,161*	*41,581*	*40,089*	*35,398*	*38,648*	*37,718*
Metallurgical Coke Production	*5,608*	*3,921*	*1,282*	*3,006*	*2,325*	*3,224*	*2,954*
Petrochemical Production	20,075	26,882	27,200	28,483	27,926	30,656	28,788
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610
Lime Production	11,700	14,552	13,106	12,112	11,299	11,870	12,208
Other Process Uses of Carbonates	7,103	8,472	7,938	8,973	9,012	8,583	10,384

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	6,113	6,150	5,805	6,600	7,053
Carbon Dioxide Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704
Titanium Dioxide Production	1,195	1,755	1,541	1,340	1,340	1,474	1,474
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446
Ferroalloy Production	2,152	1,392	2,063	1,598	1,377	1,567	1,327
Zinc Production	632	1,030	999	1,026	977	1,007	947
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840
Lead Production	516	553	527	531	450	439	428
Carbide Production and Consumption	243	213	184	175	154	172	210
Substitution of Ozone Depleting Substances[a]	+	1	3	3	4	4	4
Magnesium Production and Processing	129	4	2	2	3	3	3
CH_4	**3**	**2**	**2**	**1**	**1**	**1**	**1**
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**112**	**84**	**87**	**71**	**79**	**74**	**61**
Nitric Acid Production	41	38	32	34	31	30	33
N_2O from Product Uses	*14*	*14*	*14*	*14*	*14*	*14*	*14*
Adipic Acid Production	51	24	35	18	28	25	8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	5	5	4	5	5
Electronics Industry	+	+	1	1	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**101**	**83**	**179**	**173**	**167**	**139**	**172**
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Aluminum Production	M	M	M	M	M	M	M
SF_6 and PFCs from Other Product Use	101	83	178	173	167	138	172
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0	+	+	+	+
SF_6	**2**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	1	1	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+

Gas/Source	1990	2005	2018	2019	2020	2021	2022
SF_6 and PFCs from Other Product Use	0	0	+	+	+	+	+
Fluorochemical Production	0	0	+	+	+	+	+
NF_3	**+**	**0**	**+**	**0**	**0**	**0**	**0**
Electronics Industry	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M (Mixture of gases)

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

Note: Totals by gas may not sum due to independent rounding.

This chapter presents emission estimates calculated in accordance with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its refinements. For additional detail on IPPU sources that are not included in this *Inventory* report, please review Annex 5, Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included. These sources are not included due to various national circumstances, such as emissions from a source may not currently occur in the United States, data are not currently available for those emission sources (e.g., glyoxal and glyoxylic acid production, CH_4 from direct reduced iron production), emissions are included elsewhere within the *Inventory* report, or data suggest that emissions are not significant (e.g., other various fluorinated gas emissions from other product uses). In terms of geographic scope, emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from District of Columbia and U.S. Territories to the extent to which industries are occurring. While most IPPU sources do not occur in U.S. Territories (e.g., electronics manufacturing does not occur in U.S. Territories), they are estimated and accounted for where they are known to occur (e.g., cement production, lime production, electrical equipment). EPA will review this on an ongoing basis to ensure emission sources are included across all geographic areas if they occur. Information on planned improvements for specific IPPU source categories can be found in the Planned Improvements section of the individual source category.

In addition, as mentioned in the Energy chapter of this report (Box 3-5), fossil fuels consumed for non-energy uses for primary purposes other than combustion for energy (including lubricants, paraffin waxes, bitumen asphalt, and solvents) are reported in the Energy chapter. According to the *2006 IPCC Guidelines*, these non-energy uses of fossil fuels are to be reported under the IPPU, rather than the Energy sector; however, due to national circumstances regarding the allocation of energy statistics and carbon balance data, the United States reports these non-energy uses in the Energy chapter of this *Inventory*. Although emissions from these non-energy uses are reported in the Energy chapter, the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines* and are well documented and scientifically based. The methodologies used are described in Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance, and avoid double counting. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, and emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. For more information, see the Methodology discussion in Section 3.1, CO_2 from Fossil Fuel Combustion, Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Finally, as stated in the Energy chapter, portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—are

reallocated to the IPPU chapter, as they are consumed during non-energy related industrial process activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances. This approach is compatible with the *2006 IPCC Guidelines* and is well documented and scientifically based. The emissions from these feedstocks and reducing agents are reported under the IPPU chapter to improve transparency and to avoid double counting of emissions under both the Energy and IPPU sectors. More information on the methodology to adjust for these emissions within the Energy chapter is described in the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. Additional information is listed within each IPPU emission source in which this approach applies.

Box 4-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the IPPU chapter do not preclude alternative examinations. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from industrial processes and from the use of greenhouse gases in products.

QA/QC and Verification Procedures

The quality of IPPU source categories is assured through application of the U.S. Inventory QA/QC plan outlined in Annex 8. Two types of checks were performed using this plan: (1) general (Tier 1) procedures consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking, and archiving the data, supporting documents, and files; and (2) source category-specific (Tier 2) procedures that focus on checks and comparisons of the emission factors, activity data, and methodologies used for estimating emissions from the relevant industrial process and product use sources. Examples of these procedures include: checks to ensure that activity data and emission estimates are consistent with historical trends; that consistent, complete and data sources are used and documented; that interpolation or extrapolation techniques are consistent across sources; and that common units, and conversion factors are used where applicable. Consistent with the *2006 IPCC Guidelines*, additional category-specific QC procedures were performed for more significant emission categories or sources where significant methodological and data updates have taken place. Any significant findings and errors identified are documented and corrected. Application of these procedures, specifically category-specific QC procedures and updates/improvements as a result of QA processes (expert, public, and UNFCCC technical expert reviews), are described further within respective source categories, in the Recalculations Discussion and Planned Improvement sections.

For sources that use data from EPA's Greenhouse Gas Reporting Program (GHGRP), EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic

checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[3] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with the general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. See Box 4-2 below for more information on use of GHGRP data in this chapter.

For most IPPU categories, activity data are obtained via aggregation of facility-level data from EPA's GHGRP (see Box 4-2 below and Annex 9), national commodity surveys conducted by U.S. Geological Survey (USGS) National Minerals Information Center, U.S. Department of Energy (DOE), U.S. Census Bureau, and industry associations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Chemistry Council (ACC), and American Iron and Steel Institute (AISI) (specified within each source category). The emission factors used include those derived from the EPA's GHGRP and application of IPCC default factors.

Box 4-2: Industrial Process and Product Use Data from EPA's Greenhouse Gas Reporting Program

EPA collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases.

In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were collected for facilities subject to 40 CFR Part 98, though some source categories first collected data for calendar year 2011. For more information, see Annex 9, Use of EPA Greenhouse Gas Reporting Program in Inventory.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this *Inventory*, consistent with IPCC guidelines (e.g., minerals, chemicals, product uses). Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods; however, it should be noted that the coverage and definitions for source categories (e.g., allocation of energy and IPPU emissions) in EPA's GHGRP may differ from those used in this *Inventory* in meeting the Paris Agreement and UNFCCC reporting guidelines (IPCC 2011) and is an important consideration when incorporating GHGRP data in the *Inventory*. In line with the Paris Agreement and UNFCCC reporting guidelines, the *Inventory* is a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines*. EPA has paid particular attention to ensuring both completeness and time-series consistency for major recalculations that have occurred from the incorporation of GHGRP data into these categories, consistent with *2006 IPCC Guidelines* and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories.*[4]

For certain source categories in this *Inventory* (e.g., nitric acid production, lime production, cement production, petrochemical production, carbon dioxide consumption, ammonia production, and urea consumption for non-agricultural purposes), EPA has integrated data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is

[3] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[4] See https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

only publishing data values that meet these aggregation criteria.[5] Specific uses of aggregated facility-level data are described in the respective methodological sections (e.g., including other sources using GHGRP data that is not aggregated CBI, such as aluminum, electronics industry, electrical equipment, HCFC-22 production, and magnesium production and processing). For other source categories in this chapter, as indicated in the respective planned improvements sections,[6] EPA is continuing to analyze how facility-level GHGRP data may be used to improve the national estimates presented in this *Inventory*, giving particular consideration to ensuring time-series consistency and completeness.

Additionally, EPA's GHGRP has and will continue to enhance QA/QC procedures and assessment of uncertainties within the IPPU categories (see those categories for specific QA/QC details regarding the use of GHGRP data).

4.1 Cement Production (CRT Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of carbon dioxide (CO_2) both from the energy consumed in making the clinker precursor to cement and from the chemical process to make the clinker. This reporting category (2A1) includes emissions from production of clinker and use of cement kiln dust. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of cement are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

During the clinker production process, the key reaction occurs when calcium carbonate ($CaCO_3$), in the form of limestone or similar rocks or in the form of cement kiln dust (CKD), is heated in a cement kiln at a temperature range of about 700 to 1,000 degrees Celsius (1,300 to 1,800 degrees Fahrenheit) to form lime (i.e., calcium oxide, or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during clinker production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ heated in the clinker kiln forms one mole of CaO and one mole of CO_2. The CO_2 is vented to the atmosphere as part of the kiln exhaust:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Next, over a temperature range of 1000 to 1450 degrees Celsius, the CaO combines with alumina, iron oxide and silica that are also present in the clinker raw material mix to form hydraulically reactive compounds within white-hot semifused (sintered) nodules of clinker. These "sintering" reactions are highly exothermic and produce few CO_2 process emissions. The clinker is then rapidly cooled to maintain quality and then very finely ground with a small amount of gypsum and potentially other materials (e.g., ground granulated blast furnace slag, etc.) to make portland and similar cements.

Masonry cement consists of plasticizers (e.g., ground limestone, lime, etc.) and portland cement, and the amount of portland cement used accounts for approximately 3 percent of total clinker production (USGS 2023b; 2023c). No

[5] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[6] Ammonia production, glass production, lead production, and other fluorinated gas production.

additional emissions are associated with the production of masonry cement. Carbon dioxide emissions that result from the production of lime used to produce portland and masonry cement are included in Section 4.2.

Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States. Cement is produced in 34 states and Puerto Rico. Texas, Missouri, California, and Florida were the leading cement-producing states in 2022 and accounted for approximately 43 percent of total U.S. production (USGS 2023b). In 2022, shipments of cement were estimated to have increased by about 3 percent from 2021, and net imports increased by about 17 percent compared to 2021 (USGS 2023b).

In 2022, U.S. clinker production totaled 80,500 kilotons, which was an increase of 1 percent compared to 2021 and an increase of 25 percent compared to 1990 (EPA 2023). The resulting CO_2 emissions were estimated to be 41.9 MMT CO_2 Eq. (41,884 kt) (see Table 4-3 and Table 4-4). The total construction value and cement shipments increased by 11 percent and 4 percent, respectively, during the first nine months of 2022 compared to the same time period in 2021. This increase was attributed to continued economic recovery from the COVID-19 pandemic and the November 2021 passage of the Bipartisan Infrastructure Law. Despite the increases, growth was constrained by increased costs, labor and production shortages, and ongoing supply chain disruptions (USGS 2023b).

Table 4-3: CO_2 Emissions from Cement Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9

Table 4-4: CO_2 Emissions from Cement Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884

Greenhouse gas emissions from cement production, which are primarily driven by production levels, increased every year from 1991 through 2006 but decreased in the following years until 2009. Emissions from cement production were at their highest levels in 2006 and at their lowest levels in 2009. Emissions in 2009 were approximately 28 percent lower than 2008 emissions and 12 percent lower than 1990 due to the economic recession and the associated decrease in demand for construction materials. Since 2009, emissions have increased by 41 percent due to increasing demand for cement. Cement continues to be a critical component of the construction industry; therefore, the availability of public and private construction funding, as well as overall economic conditions, have considerable impact on the level of cement production.

Methodology and Time-Series Consistency

Carbon dioxide emissions from cement production are estimated using the Tier 2 method from the *2006 IPCC Guidelines* as this is a key category, in accordance with the IPCC methodological decision tree and available data. The Tier 2 methodology was used because detailed and complete data (including weights and composition) for carbonate(s) consumed in clinker production are not available,[7] and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime mass fraction for clinker of 65 percent and a constant reflecting the mass of CO_2 released per unit of lime. The U.S. Geological Survey (USGS) mineral commodity expert for cement has confirmed that this is a reasonable assumption for the United States (Van Oss 2013a). This calculation yields an emission factor of 0.510 tons of CO_2 per ton of clinker produced, which was determined as follows:

[7] As discussed further under "Planned Improvements," most cement-producing facilities that report their emissions to the GHGRP use CEMS to monitor combined process and fuel combustion emissions for kilns, making it difficult to quantify the process emissions on a facility-specific basis. By the end of 2022, the percentage of facilities not using CEMS was 1 percent.

Equation 4-1: *2006 IPCC Guidelines* Tier 1 Emission Factor for Clinker (precursor to Equation 2.4)

$$EF_{clinker} = 0.650\ CaO \times \left[\left(44.01 \frac{g}{mole} CO_2\right) \div \left(56.08 \frac{g}{mole} CaO\right)\right] = 0.510 \frac{\text{tons } CO_2}{\text{ton clinker}}$$

During clinker production, some of the raw materials, partially reacted raw materials, and clinker enters the kiln line's exhaust system as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). To the degree that the CKD contains carbonate raw materials which are then calcined, there are associated CO_2 emissions. At some plants, essentially all CKD is directly returned to the kiln, becoming part of the raw material feed, or is likewise returned to the kiln after first being removed from the exhaust. In either case, the returned CKD becomes a raw material, thus forming clinker, and the associated CO_2 emissions are a component of those calculated for the clinker overall. At some plants, however, the CKD cannot be returned to the kiln because it is chemically unsuitable as a raw material or chemical issues limit the amount of CKD that can be so reused. Any clinker that cannot be returned to the kiln is either used for other (non-clinker) purposes or is landfilled. The CO_2 emissions attributable to the non-returned calcinated portion of the CKD are not accounted for by the clinker emission factor and thus a CKD correction factor should be applied to account for those emissions. The USGS reports the amount of CKD used to produce clinker, but no information is currently available on the total amount of CKD produced annually.[8] Because data are not currently available to derive a country-specific CKD correction factor, a default correction factor of 1.02 (2 percent) was used to account for CKD CO_2 emissions, as recommended by the IPCC (IPCC 2006).[9] Total cement production emissions were calculated by adding the emissions from clinker production and the emissions assigned to CKD.

Small amounts of impurities (i.e., not calcium carbonate) may exist in the raw limestone used to produce clinker. The proportion of these impurities is generally minimal, although a small amount (1 to 2 percent) of magnesium oxide (MgO) may be desirable as a flux. Per the IPCC Tier 2 methodology, a correction for MgO is not used, since the amount of MgO from carbonate is likely very small and the assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006).

The 1990 through 2012 activity data for clinker production were obtained from USGS (Van Oss 2013a; Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014). USGS compiled the data (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including facilities in Puerto Rico. Clinker production values in the current *Inventory* report utilize GHGRP data for the years 2014 through 2022 (EPA 2023). Clinker production data are summarized in Table 4-5. Details on how this GHGRP data compares to USGS reported data can be found in the section on QA/QC and Verification.

Table 4-5: Clinker Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Clinker Production	64,355	88,783	74,900	78,600	78,200	79,400	80,500

Note: Clinker production from 1990 through 2022 includes Puerto Rico (relevant U.S. Territories).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. The methodology for cement production spliced activity data from two different sources: USGS for

[8] The USGS *Minerals Yearbook: Cement* notes that CKD values used for clinker production are likely underreported.

[9] As stated on p. 2.12 of the *2006 IPCC Guidelines*, Vol. 3, Chapter 2: "…As data on the amount of CKD produced may be scarce (except possibly for plant-level reporting), estimating emissions from lost CKD based on a default value can be considered good practice. The amount of CO_2 from lost CKD can vary but range typically from about 1.5 percent (additional CO_2 relative to that calculated for clinker) for a modern plant to about 20 percent for a plant losing a lot of highly calcinated CKD (van Oss 2005). In the absence of data, the default CKD correction factor (CF_{ckd}) is 1.02 (i.e., add 2 percent to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the CKD correction factor will be 1.00 (van Oss 2005)…"

1990 through 2013 and GHGRP starting in 2014. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent; 65 percent is used as a representative value (Van Oss 2013a). This contributes to the uncertainty surrounding the emission factor for clinker which has an uncertainty range of ±3 percent with uniform densities (Van Oss 2013b). The amount of CO_2 from CKD loss can range from 1.5 to 8 percent depending upon plant specifications, and uncertainty was estimated at ±5 percent with uniform densities (Van Oss 2013b). Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of the total thickness. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated. EPA assigned uncertainty bounds of ±3 percent and a normal probability density function for clinker production and uncertainty bounds of ±5 percent and a uniform probability density function for the emission factor, based on expert judgment (Van Oss 2013b).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-6. Based on the uncertainties associated with total U.S. clinker production, the CO_2 emission factor for clinker production, and the emission factor for additional CO_2 emissions from CKD, 2022 CO_2 emissions from cement production were estimated to be between 40.1 and 43.8 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 4 percent below and 5 percent above the emission estimate of 41.9 MMT CO_2 Eq.

Table 4-6: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate [a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	41.9	40.1	43.8	-4%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

EPA relied upon the latest guidance from the IPCC on the use of facility-level data in national inventories and applied a category-specific QC process to compare activity data from EPA's GHGRP with existing data from USGS surveys. This was to ensure time-series consistency of the emission estimates presented in the *Inventory*. Total U.S. clinker production is assumed to have low uncertainty because facilities routinely measure this for economic reasons and because both USGS and GHGRP take multiple steps to ensure that reported totals are accurate. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the reporting industry (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year

comparison checks, along with manual reviews involving outside data checks) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[10] Facilities are also required to monitor and maintain records of monthly clinker production per section 98.84 of the GHGRP regulation (40 CFR 98.84).

EPA's GHGRP requires all facilities producing portland cement to report greenhouse gas emissions, including CO_2 process emissions from each kiln, CO_2 combustion emissions from each kiln, CH_4 and N_2O combustion emissions from each kiln, and CO_2, CH_4, and N_2O emissions from each stationary combustion unit other than kilns (40 CFR Part 98 Subpart H). Source-specific quality control measures for the cement production category are included in section 98.84, Monitoring and QA/QC Requirements.

As mentioned above, EPA compares GHGRP clinker production data (EPA 2023) to the USGS clinker production data (USGS 2023a; USGS 2023c). For the year 2014, 2020, and 2022, USGS and GHGRP clinker production data showed a difference of approximately 1 percent. In 2018, the difference between USGS and GHGRP clinker production data was approximately 3 percent, which resulted in a difference in emissions of about 1.2 MMT CO_2 Eq. In 2015, 2016, 2017, 2019, and 2021, that difference was less than 0.5 percent (less than 0.2 MMT CO_2 Eq.) between the two sets of activity data. The information collected by the USGS National Minerals Information Center surveys continue to be an important data source.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Cement Production source category. Most cement production facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor and report CO_2 emissions, thus reporting combined process and combustion emissions from kilns. In implementing further improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon, in addition to category-specific QC methods recommended by the *2006 IPCC Guidelines*.[11] EPA's long-term improvement plan includes continued assessment of the feasibility of using additional GHGRP information beyond aggregation of reported facility-level clinker data, in particular disaggregating the combined process and combustion emissions reported using CEMS, to separately present national process and combustion emissions streams consistent with IPCC and UNFCCC guidelines. This long-term planned analysis is still in development and has not been applied for this current *Inventory*.

EPA continues to review methods and data used to estimate CO_2 emissions from cement production in order to account for organic material in the raw material and to discuss the carbonation that occurs across the duration of the cement product. Work includes identifying data and studies on the average carbon content for organic materials in kiln feed in the United States and on CO_2 reabsorption rates via carbonation for various cement products. This information is not reported by facilities subject to GHGRP reporting. This is a long-term improvement.

[10] See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[11] See IPCC Technical Bulletin on Use of Facility-Specific Data in National Greenhouse Gas Inventories http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.2 Lime Production (CRT Source Category 2A2)

Lime is a manufactured product with many industrial, chemical, and environmental applications. This reporting category (2A2) includes process emissions from the production of lime. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lime are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide (CO_2) is generated during the calcination stage, when limestone—consisting of calcium carbonate ($CaCO_3$) and/or magnesium carbonate ($MgCO_3$)—is roasted at high temperatures in a kiln to produce calcium oxide (CaO) and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere.

$$CaCO_3 \rightarrow CaO + CO_2$$

Some facilities, however, recover CO_2 generated during the production process for use in sugar refining and precipitated calcium carbonate (PCC) production.[12] PCC is used as a filler or coating in the paper, food, and plastic industries and is derived from reacting hydrated high-calcium quicklime with CO_2, a production process that does not result in net emissions of CO_2 to the atmosphere.

For U.S. operations, the term "lime" refers to a variety of chemical compounds. These include CaO, or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

The current lime market is approximately distributed across six end-use categories, as follows: metallurgical uses, 35 percent; environmental uses, 29 percent; chemical and industrial uses, 21 percent; construction uses, 10 percent; miscellaneous uses, 3 percent; and refractory dolomite, 1 percent (USGS 2021). The major uses are in steel making, chemical and industrial applications (such as the manufacture of fertilizer, glass, paper and pulp, and precipitated calcium carbonate, and in sugar refining), flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water treatment, as well as uses in mining, pulp and paper and precipitated calcium carbonate manufacturing (USGS 2023a). Lime is also used as a CO_2 scrubber, and there has been experimentation on the use of lime to capture CO_2 from electric power plants. Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from limestone consumption for FGD systems are reported under Section 4.4 Other Process Uses of Carbonate Production (CRT Source Category 2A4).

Emissions from lime production have fluctuated over the time series depending on lime end-use markets – primarily the steel making industry and FGD systems for utility and industrial plants – and also energy costs. One significant change to lime end-use since 1990 has been the increase in demand for lime for FGD at coal-fired electric power plants, which can be attributed to compliance with sulfur dioxide (SO_2) emission regulations of the Clean Air Act Amendments of 1990. Phase I went into effect on January 1, 1995, followed by Phase II on January 1, 2000. To supply lime for the FGD market, the lime industry installed more than 1.8 million tons per year of new capacity by the end of 1995 (USGS 2023a). The need for air pollution controls continued to drive the FGD lime market, which had doubled between 1990 and 2019 (2021, 2023a, 2023b).

The U.S. lime industry temporarily shut down some individual gas-fired kilns and, in some case, entire lime plants during 2000 and 2001, due to significant increases in the price of natural gas. Lime production continued to

[12] The amount of CO_2 captured from lime production for sugar refining and PCC production is reported under CRT Source Category 2H3 "Other", but within this report, they are included in this chapter.

decrease in 2001 and 2002, a result of lower demand from the steel making industry, lime's largest end-use market, when domestic steel producers were affected by low priced imports and slowing demand (USGS 2023a).

Emissions from lime production peaked in 2006 at approximately 30.3 percent above 1990 levels, due to strong demand from the steel and construction markets (road and highway construction projects), before dropping to its second lowest level in 2009 at approximately 2.5 percent below 1990 emissions, driven by the economic recession and downturn in major markets including construction, mining, and steel (USGS 2023a). In 2010, the lime industry began to recover as the steel, FGD, and construction markets also recovered (USGS 2023a). Fluctuation in lime production since 2015 has been driven largely by demand from the steel making industry (USGS 2021). In 2020, a significant decline in lime production occurred due to plants temporarily closing as a result of the global COVID-19 pandemic (USGS 2023a). This resulted in the lowest level of emissions in 2020 at approximately 3.4 percent below 1990 emissions. Emissions increased annually since then, with 2022 levels similar to emissions in 2019.

Lime production in the United States—including Puerto Rico—was reported to be 16,994 kilotons in 2022, an increase of about 1.3 percent compared to 2021 levels (USGS 2023a). Compared to 1990, lime production increased by about 7.3 percent. At year-end 2022, 73 primary lime plants were operating in the United States, including Puerto Rico (USGS 2023a).[13] Principal lime producing states were, in alphabetical order, Kentucky, Missouri, Ohio, and Texas (USGS 2023a).

U.S. lime production resulted in estimated net CO_2 emissions of 12.2 MMT CO_2 Eq. (12,208 kt) (see Table 4-7 and Table 4-8). Carbon dioxide emissions from lime production increased by about 2.8 percent compared to 2021 levels. Compared to 1990, CO_2 emissions have increased by about 4.3 percent. The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described above.

Table 4-7: CO_2 Emissions from Lime Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2

Table 4-8: Gross, Recovered, and Net CO_2 Emissions from Lime Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Gross	11,959	15,074	13,609	12,676	11,875	12,586	12,750
Recovered[a]	259	522	503	564	576	716	542
Net Emissions	**11,700**	**14,552**	**13,106**	**12,112**	**11,299**	**11,870**	**12,208**

Note: Totals may not sum due to independent rounding.

[a] For sugar refining and PCC production.

Methodology and Time-Series Consistency

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors, consistent with Tier 2 methodology from the *2006 IPCC Guidelines* and in accordance with the IPCC methodological decision tree and available data. The emission factor is the product of the stoichiometric ratio between CO_2 and CaO, and the average CaO and MgO content for lime. The CaO and MgO content for lime is assumed to be 95 percent for both high-calcium and dolomitic lime (IPCC 2006). The emission factors were calculated as follows:

[13] In 2022, 68 operating primary lime facilities in the United States reported to the EPA Greenhouse Gas Reporting Program.

Equation 4-2: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, High-Calcium Lime (Equation 2.9)

$$EF_{\text{High-Calcium Lime}} = \left[\left(44.01 \frac{\text{g}}{\text{mole}} CO_2\right) \div \left(56.08 \frac{\text{g}}{\text{mole}} CaO\right)\right] \times \left(0.9500 \frac{CaO}{\text{lime}}\right) = 0.7455 \frac{\text{g } CO_2}{\text{g lime}}$$

Equation 4-3: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, Dolomitic Lime (Equation 2.9)

$$EF_{\text{Dolomitic Lime}} = \left[\left(88.02 \frac{\text{g}}{\text{mole}} CO_2\right) \div \left(96.39 \frac{\text{g}}{\text{mole}} CaO \bullet MgO\right)\right] \times \left(0.9500 \frac{CaO \bullet MgO}{\text{lime}}\right) = 0.8675 \frac{\text{g } CO_2}{\text{g lime}}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to ($Ca(OH)_2$ and $[Ca(OH)_2 \bullet Mg(OH)_2]$) (IPCC 2006). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 30 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD) through application of a correction factor. LKD is a byproduct of the lime manufacturing process typically not recycled back to kilns. LKD is a very fine-grained material and is especially useful for applications requiring very small particle size. Most common LKD applications include soil reclamation and agriculture. Emissions from the application of lime for agricultural purposes are reported in the Agriculture chapter under 5.5 Liming (CRT Source Category 3G). Currently, data on annual LKD production is not readily available to develop a country-specific correction factor. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006). See the Planned Improvements section associated with efforts to improve uncertainty analysis and emission estimates associated with LKD.

Lime emission estimates were further adjusted to account for the amount of CO_2 captured for use in on-site processes. All the domestic lime facilities are required to report these data to EPA under its GHGRP. The total national-level annual amount of CO_2 captured for on-site process use was obtained from EPA's GHGRP (EPA 2023) based on reported facility-level data for years 2010 through 2022. The amount of CO_2 captured/recovered for non-marketed on-site process use is deducted from the total gross emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-7 and Table 4-8. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2022. Since GHGRP data are not available for 1990 through 2009, IPCC "splicing" techniques were used as per the *2006 IPCC Guidelines* on time-series consistency (IPCC 2006, Volume 1, Chapter 5).

Lime production data (i.e., lime sold and non-marketed lime used by the producer) by type (i.e., high-calcium and dolomitic quicklime, high-calcium and dolomitic hydrated lime, and dead-burned dolomite) for 1990 through 2022 (see Table 4-9) were obtained from U.S. Geological Survey (USGS) *Minerals Yearbook* (USGS 2023a) and are compiled by USGS to the nearest ton. Dead-burned dolomite data are additionally rounded by USGS to no more than one significant digit to avoid disclosing company proprietary data. Production data for the individual quicklime (i.e., high-calcium and dolomitic) and hydrated lime (i.e., high-calcium and dolomitic) types were not provided prior to 1997. These were calculated based on total quicklime and hydrated lime production data from 1990 through 1996 and the three-year average ratio of the individual lime types from 1997 to 1999. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2023a). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent based on recommendations from the IPCC and using the water content values for high-calcium hydrated lime and dolomitic hydrated lime mentioned above, and is presented in Table 4-10 (IPCC 2006). The CaO and CaO•MgO contents of lime, both 95 percent, were obtained from the IPCC (IPCC 2006).

Table 4-9: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium Quicklime	11,166	14,100	12,400	11,300	10,700	11,200	11,500
Dolomitic Quicklime	2,234	2,990	2,810	2,700	2,390	2,700	2,640
High-Calcium Hydrated	1,781	2,220	2,430	2,430	2,320	2,430	2,410
Dolomitic Hydrated	319	474	265	267	252	244	244
Dead-Burned Dolomite	342	200	200	200	200	200	200

Table 4-10: Adjusted Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium	12,466	15,721	14,174	13,074	12,394	12,974	13,259
Dolomitic	2,800	3,522	3,196	3,087	2,766	3,071	3,011

Note: Minus water content of hydrated lime.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2, whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO_2 that is reabsorbed would require a detailed accounting of lime use in the United States and additional information about the associated processes where both the lime and byproduct CO_2 are "reused." Research conducted thus far has not yielded the necessary information to quantify CO_2 reabsorption rates.[14] Some additional information on the amount of CO_2 consumed on site at lime facilities, however, has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[15] The lime generated by these processes is included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic carbon (C) is present from the wood. Kraft

[14] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[15] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$], and no CO_2 is released.

mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin and therefore is not included in the industrial processes totals (Miner and Upton 2002). In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands (see the Land Use, Land-Use Change, and Forestry chapter).

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. EPA assigned uncertainty ranges of ±2 percent and a triangular probability density function for the LKD correction factor based on expert judgment (RTI 2023). The National Lime Association (NLA) has commented that the estimates of emissions from LKD in the United States could be closer to 6 percent. They also note that additional emissions (approximately 2 percent) may also be generated through production of other byproducts/wastes (off-spec lime that is not recycled, scrubber sludge) at lime plants (Seeger 2013). Publicly available data on LKD generation rates, total quantities not used in cement production, and types of other byproducts/wastes produced at lime facilities are limited. NLA compiled and shared historical emissions information and quantities for some waste products reported by member facilities associated with generation of total calcined byproducts and LKD, as well as methodology and calculation worksheets that member facilities complete when reporting. There is uncertainty regarding the availability of data across the time series needed to generate a representative country-specific LKD factor. Uncertainty of the activity data is also a function of the reliability and completeness of voluntarily reported plant-level production data. EPA assigned uncertainty ranges of ±1 percent for lime production and a normal probability density function, based on expert judgment (USGS 2012). Further research, including discussion with NLA, and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on the *2006 IPCC Guidelines*. More information can be found in the Planned Improvements section below.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-11. Lime CO_2 emissions for 2022 were estimated to be between 12.1 and 12.3 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 1 percent below and 1 percent above the emission estimate of 12.2 MMT CO_2 Eq.

Table 4-11: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	12.2	12.1	12.3	-1%	+1%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as noted in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods associated with reporting on CO_2 captured for onsite use applicable to lime manufacturing facilities can be found under Subpart S (lime

manufacturing) of the GHGRP regulation (40 CFR Part 98).[16]EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2023).[17] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review GHGRP emissions and activity data reported to EPA under Subpart S of the GHGRP regulation (40 CFR Part 98), and aggregated activity data on lime production by type in particular. In addition, initial review of data has identified that several facilities use CEMS to report emissions. Under Subpart S, if a facility is using a CEMS, they are required to report combined combustion emissions and process emissions. EPA continues to review how best to incorporate GHGRP and notes that particular attention will be made to also ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required because the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[18]

Future improvements involve improving and/or confirming the representativeness of current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty section, per comments from the NLA provided during a prior Public Review comment period for a previous (1990 through 2018) *Inventory.* EPA met with NLA in summer of 2020 for clarification on data needs and available data and to discuss planned research into GHGRP data. Previously, EPA met with NLA in spring of 2015 to outline specific information required to apply IPCC methods to develop a country-specific correction factor to more accurately estimate emissions from production of LKD. In 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives from 2002 through 2011 associated with generation of total calcined byproducts and LKD. Reporting of LKD was only differentiated for the years 2010 and 2011. This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol, which was also provided to EPA. To reflect information provided by NLA, EPA updated the qualitative description of uncertainty. At the time of this *Inventory*, this planned improvement is in process and has not been incorporated into this current *Inventory* report.

[16] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[17] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[18] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.3 Glass Production (CRT Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making glass and the glass production process itself. This reporting category (2A3) includes emissions from the production of glass. Emissions from fuels consumed for energy purposes during the production of glass are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Glass production employs a variety of raw materials in a glass-batch. These include formers, fluxes, stabilizers, and sometimes colorants. The major raw materials (i.e., fluxes and stabilizers) that emit process-related CO_2 emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO_2). Other major formers in glass include feldspar and boric acid (i.e., borax). Fluxes are added to lower the temperature at which the batch melts. Most commonly used flux materials are soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2O). Stabilizers make glass more chemically stable and keep the finished glass from dissolving and/or falling apart. Commonly used stabilizing agents in glass production are limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$), alumina (Al_2O_3), magnesia (MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO_3$), lithium carbonate (Li_2CO_3), and zirconia (ZrO_2) (DOE 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the production process or other glass spillage or retention, such as recycling or from cullet broker services.

The raw materials (primarily soda ash, limestone, and dolomite) release CO_2 emissions in a complex high-temperature chemical reaction during the glass melting process. This process is not directly comparable to the calcination process used in lime manufacturing, cement manufacturing, and process uses of carbonates (i.e., limestone/dolomite use) but has the same net effect in terms of generating process CO_2 emissions (IPCC 2006).

The U.S. glass industry can be divided into four main categories: containers, flat (window) glass, fiber glass, and specialty glass. The majority of commercial glass produced is container and flat glass (EPA 2009). The United States is one of the major global exporters of glass. Domestically, demand comes mainly from the construction, auto, bottling, and container industries. There are more than 1,700 facilities that manufacture glass in the United States, with the largest companies being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[19]

The glass container sector is one of the leading soda ash consuming sectors in the United States. In 2022, glass production accounted for 49 percent of total domestic soda ash consumption (USGS 2023). Emissions from soda ash production are reported in Section 4.12.

In 2022, 2,250 kilotons of soda ash, 1,370 kilotons of limestone, 925 kilotons of dolomite, and 1.9 kilotons of other carbonates were consumed for glass production (USGS 2023; EPA 2023). Use of soda ash, limestone, dolomite, and other carbonates in glass production resulted in aggregate CO_2 emissions of 2.0 MMT CO_2 Eq. (1,956 kt), which are summarized in Table 4-12 and Table 4-13. Overall, emissions have decreased by 14 percent compared to 1990. Emissions decreased by 1 percent compared to 2021 levels.

Emissions from glass production have remained relatively consistent over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. Specifically, the extended downturn in residential and commercial construction and automotive industries between 2008 and 2010 resulted in reduced consumption of glass products, causing a drop in global demand for limestone, dolomite, and soda ash and resulting in lower emissions. Some commercial food and beverage package

[19] Excerpt from Glass & Glass Product Manufacturing Industry Profile, First Research. Available online at: http://www.firstresearch.com/Industry-Research/Glass-and-Glass-Product-Manufacturing.html.

manufacturers are shifting from glass containers towards lighter and more cost-effective polyethylene terephthalate (PET) based containers, putting downward pressure on domestic consumption of soda ash (USGS 1995 through 2015b). Glass production in 2022 was steady, changing by no more than 2 percent over the course of the year (Federal Reserve 2023).

Table 4-12: CO_2 Emissions from Glass Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0

Table 4-13: CO_2 Emissions from Glass Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956

Methodology and Time-Series Consistency

Carbon dioxide emissions were calculated based on Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by the carbonate-based emission factor (in metric tons CO_2/metric ton carbonate) and the average carbonate-based mineral mass fraction.

2010 through 2022

The methodology for estimating CO_2 emissions from glass production for years 2010 through 2022 used the quantities of limestone, dolomite, and a group of other carbonates (i.e., barium carbonate, potassium carbonate, lithium carbonate, and strontium carbonate) used for glass production, obtained from GHGRP (EPA 2023). USGS data on the quantity of soda ash used for glass production was used because it was obtained directly from the soda ash producers and includes use by smaller artisanal glass operations, which are excluded in the GHGRP data.

GHGRP collects data from glass production facilities with greenhouse gas emissions greater than 25,000 metric tons CO_2 Eq. The reporting threshold is used to exclude artisanal glass operations that are expected to have much lower greenhouse gas emissions than the threshold. These smaller facilities have not been accounted for yet for this portion of the time series for limestone, dolomite, or other carbonates due to limited data. Facilities report the total quantity of each type of carbonate used in glass production each year to GHGRP, with data collection starting in 2010 (EPA 2023).

Using the total quantities of each carbonate, EPA calculated the metric tons of emissions resulting from glass production by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by carbonate-based emission factors in metric tons CO_2/metric ton carbonate (limestone, 0.43971; dolomite, 0.47732; soda ash, 0.41492; and other carbonates, 0.262), and by the average carbonate-based mineral mass fraction for each year. IPCC default emission factors were used for limestone, dolomite, and soda ash, and the emission factor for other carbonates is based on expert judgment (RTI 2022).

1990 through 2009

Data from GHGRP on the quantity of limestone, dolomite, and other carbonates used in glass production are not available for 1990 through 2009. Additionally, USGS does not collect data on the quantity of other carbonates used for glass production.

To address time-series consistency, total emissions from 1990 to 2009 were calculated using the Federal Reserve Industrial Production Index for glass production in the United States as a surrogate for the total quantity of carbonates used in glass production. The production index measures real output expressed as a percentage of real output in a base year, which is currently 2017 (Federal Reserve 2023). Since January 1971, the Federal Reserve has released the monthly glass production index for NAICS code 3272 (Glass and Glass Product Manufacturing) as part

of release G.17, "Industrial Production and Capacity Utilization" (Federal Reserve 2023). The monthly index values for each year were averaged to calculate an average annual glass production index value. Total annual process emissions were calculated by taking a ratio of the average annual glass production index for each year to the average annual glass production index for base year 2017, and multiplying by the calculated 2017 emissions (process-related) based on GHGRP data.

Emissions from limestone, dolomite, and other carbonate consumption were disaggregated from total annual emissions, using the average percent contribution of each to annual emissions from these three carbonates for 2010 through 2014 based on GHGRP data: 64.5 percent limestone, 35.5 percent dolomite, and 0.1 percent other carbonates.

The methodology for estimating CO_2 emissions from the use of soda ash for glass production and data sources for the amount of soda ash used in glass production are consistent with the methodology used for 2010 through 2022. The average mineral mass fractions for soda ash are only available starting in 2010. The average carbonate-based mineral mass fractions from the GHGRP, averaged across 2010 through 2014, indicate that soda ash contained 98.7 percent sodium carbonate (Na_2CO_3). This averaged value is used to estimate emissions for 1990 through 2009. The years 2010 to 2014 were used to determine the average carbonate-based mineral mass fractions because those years were deemed to better represent historic glass production from 1990 to 2009.

Data on soda ash used for glass production for 1990 through 2022 were obtained from the U.S. Bureau of Mines (1991 and 1993a), the USGS *Minerals Yearbook: Soda Ash* (USGS 1995 through 2015b), and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2017 through 2023). Data on limestone, dolomite, and other carbonates used for glass production and on average carbonate-based mineral mass fraction for 2010 through 2022 were obtained from GHGRP (EPA 2023). The quantities of limestone, dolomite, and other carbonates were calculated for 1990 through 2009 using the Federal Reserve Industrial Production Index (Federal Reserve 2023).

The amount of limestone, dolomite, soda ash, and other carbonates used in glass production each year and the annual average Federal Reserve production indices for glass production are shown in Table 4-14.

Table 4-14: Limestone, Dolomite, Soda Ash, and Other Carbonates Used in Glass Production (kt) and Average Annual Production Index for Glass and Glass Product Manufacturing

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,409	1,690	1,442	1,370	1,334	1,397	1,370
Dolomite	714	857	871	883	824	893	925
Soda Ash	3,177	3,050	2,280	2,220	2,130	2,280	2,250
Other Carbonates	2	3	2	2	2	2	1.9
Total	**5,302**	**5,599**	**4,596**	**4,475**	**4,289**	**4,572**	**4,547**
Production Index[a]	94.3	113.1	102.5	99.8	92.4	88.3	86.8

[a] Average Annual Production Index uses 2017 as the base year.

Note: Totals may not sum due to independent rounding.

As discussed above, methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare USGS and GHGRP data sets for 2010 through 2022. To address the inconsistencies, adjustments were made as described above.

Uncertainty

The methodology in this *Inventory* report uses GHGRP data for the average mass fraction of each mineral used in glass production. These minerals are limestone, dolomite, soda ash, and other carbonates (barium carbonate ($BaCO_3$), potassium carbonate (K_2CO_3), lithium carbonate (Li_2CO_3), and strontium carbonate ($SrCO_3$)). The mass fractions are reported directly by the glass manufacturers, for each year from 2010 to 2022.

The methodology uses the quantities of limestone, dolomite, and other carbonates used in glass manufacturing which is reported directly by the glass manufacturers for years 2010 through 2022 and the amount of soda ash used in glass manufacturing which is reported by soda ash producers for the full time series. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for all carbonate quantities and the Federal Reserve Industrial Production Index for glass production, and using this suggested uncertainty provided in Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for the carbonate emission factors, ±2 percent for the mineral mass fractions, and ±1 percent for the calcination fraction, and using this suggested uncertainty provided in Section 2.4.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors, mineral mass fractions, and calcination fraction.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-15. In 2022, glass production CO_2 emissions were estimated to be between 1.9 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 2.0 MMT CO_2 Eq.

Table 4-15: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Glass Production	CO_2	2.0	1.9	2.0	-2%	+2%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[20] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

During annual QC, a transcription error for the 1990 value of CO_2 emissions from glass production was identified and corrected in Table 4-12 and Table 4-13. No recalculations were needed or performed due to this transcription error, and no other recalculations were performed for the 1990 through 2021 portion of the time series.

[20] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA plans to evaluate updates to uncertainty levels for the activity data and mineral mass fraction values from EPA's GHGRP. This is a near-term planned improvement that is anticipated for inclusion in 2025 report.

Some glass producing facilities in the United States do not report to EPA's GHGRP because they fall below the reporting threshold for this industry. EPA will continue ongoing research on the availability of data to better assess the completeness of emission estimates from glass production and how to refine the methodology to ensure complete national coverage of this category. When reporting began in 2010, EPA received data from more facilities that were above the reporting threshold than expected, and total emissions for these reporting facilities were higher than expected for all glass production facilities in the United States (EPA 2009). Research will include reassessing previous assessments of GHGRP industry coverage using the reporting threshold of 25,000 metric tons CO_2 Eq. This is a medium-term planned improvement.

4.4 Other Process Uses of Carbonates (CRT Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$),[21] and other carbonates such as soda ash, magnesite, and siderite are basic materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy (i.e., iron and steel production, ferroalloy production, and magnesium production), glass production, environmental pollution control, ceramics production, and non-metallurgical magnesia production. This reporting category (2A4) includes emissions from other uses of limestone, dolomite, and other carbonates not included in other categories; the production of ceramics; other uses of soda ash not included elsewhere; and the production of non-metallurgical magnesia. This section addresses mineral industry use of these carbonates: limestone, dolomite, soda ash, and magnesite. Emissions from the use of these carbonates are organized into four subcategories: other process uses of carbonates (i.e., limestone and dolomite consumption), ceramics production, other uses of soda ash, and non-metallurgical magnesia production.

For industrial applications, carbonates are heated sufficiently enough to calcine the material and generate CO_2 as a byproduct.

$$CaCO_3 \rightarrow CaO + CO_2$$

$$MgCO_3 \rightarrow MgO + CO_2$$

Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, and as a raw material for the production of glass, lime, and cement.

Emissions from limestone and dolomite used in the production of cement, lime, glass, and iron and steel are excluded from the other process uses of carbonates category and reported under their respective source categories (e.g., Section 4.3, Glass Production). Emissions from soda ash production are reported under Section 4.12, Soda Ash Production (CRT Source Category 2B7). Emissions from soda ash consumption associated with glass manufacturing are reported under Section 4.3, Glass Production (CRT Source Category 2A3). Emissions from the use of limestone and dolomite in liming of agricultural soils are included in the Agriculture chapter under Section 5.5, Liming (CRT Source Category 3G). Emissions from limestone and dolomite used in the production of iron and steel and magnesium production are reported under Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

[21] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Emissions from dolomite used in the production of magnesium are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4). As noted in Section 4.19, Ferroalloy Production (CRT Source Category 2C2), emissions from the production of ferromanganese are not included in this *Inventory* because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Emissions from fuels consumed for energy purposes during these processes are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter in Section 3.1, Fossil Fuel Combustion (CRT Source Category 1A). Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from lime consumption for FGD systems and from sugar refining are reported under Section 4.3, Lime Production (CRT Source Category 2A2). Emissions from the use of dolomite in primary magnesium metal production are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4).

Limestone and dolomite are widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. In 2018, the leading limestone producing states were Texas, Florida, Ohio, Missouri, and Pennsylvania, which contributed 46 percent of the total U.S. output (USGS 2022a). Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Pennsylvania, New York, and Utah which currently contribute more than a third of the total U.S. output (USGS 2022a).

Ceramics include the production of bricks and roof tiles, vitrified clay pipes, refractory products, expanded clay products, wall and floor tiles, table and ornamental ware (i.e., household ceramics), sanitary ware, technical ceramics (e.g., aerospace, automotive, electronic, or biomedical applications), and inorganic bonded abrasives. Most ceramic products are made from one or more different types of clay (e.g., shales, fire clay, and ball clay) with varying carbonate contents. The process of manufacturing ceramic products, regardless of the product type or scale, is essentially the same. This process consists of raw material processing (grinding, calcining, and drying), forming (wet or dry process), firing (single or multiple stage firing process), and final processing. Process CO_2 emissions are produced during the calcination process in the kiln or dryer, where carbonates are heated to high temperatures which results in metal oxides and CO_2. In 2018, the leading clay producing states were Georgia, Wyoming, Texas, Alabama, and North Carolina, which contributed 60 percent of the total U.S. output (USGS 2022f).

Other uses of soda ash include the consumption of soda ash for non-glass purposes. Excluding glass production, soda ash consumption by end use in 2022 included chemicals, 54 percent, soap and detergent manufacturing, 9 percent; distributers, 10 percent; flue gas desulfurization, 7 percent; other uses, 17 percent; pulp and paper production, 1 percent; and water treatment, 2 percent (USGS 2023a). Chemicals produced using soda ash include sodium-based inorganic chemicals such as sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates. (USGS 2022g). Internationally, two types of soda ash are produced: natural and synthetic. In 2019, 93 percent of the global soda ash production came from China, the United States, Russia, Germany, India, Turkey, Poland, and France. The United States only produces natural soda ash and only in two states: Wyoming and California (USGS 2021a).

Non-metallurgical magnesia production comprises of three categories of magnesia products: calcined magnesia, deadburned magnesia, and fused magnesia. Magnesia is produced by calcining magnesite ($MgCO_3$) which results in the release of CO_2. Non-metallurgical magnesia is used in agricultural, industrial, refractory, and electrical insulating applications. Specific applications include fertilizers, construction materials, plastics, and flue gas desulphurization. China, Russia, and Turkey account for 83 percent of global production capacity of magnesia from magnesite (USGS 2022e). In the United States, only one facility located in Nevada produces non-metallurgical magnesia using magnesite as the raw material.

In 2022, 18,671 kilotons (kt) of limestone, 2,052 kt of dolomite, 2,391 kt of soda ash, and 388 kt of magnesite were consumed for these emissive applications, which excludes consumption for the production of cement, lime, glass, and iron and steel (Willett 2023; USGS 2022b). Usage of limestone, dolomite, soda ash, and magnesite resulted in aggregate CO_2 emissions of 10.4 MMT CO_2 Eq. (10,384 kt) (see Table 4-16 and Table 4-17). The 2022 emissions increased 21 percent compared to 2021, primarily as a result of increased limestone consumption attributed to

sulfur oxide removal. Growth in the public and private construction markets contributed to an increase in consumption of crushed stone in 2022. Overall emissions have increased 46 percent from 1990 through 2022.

Table 4-16: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4.8	6.2	6.3	7.4	7.4	7.0	8.8
Ceramics Production	0.8	0.8	0.4	0.4	0.4	0.4	0.4
Other Uses of Soda Ash[a]	1.4	1.3	1.1	1.0	1.0	1.0	1.0
Non-Metallurgical Magnesia Production	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Total	**7.1**	**8.5**	**7.9**	**9.0**	**9.0**	**8.6**	**10.4**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Table 4-17: CO_2 Emissions from Other Process Uses of Carbonates (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4,843	6,155	6,283	7,386	7,441	6,972	8,781
Ceramics Production	757	822	418	399	397	400	407
Other Uses of Soda Ash[a]	1,390	1,305	1,069	1,036	958	979	992
Non-Metallurgical Magnesia Production	113	191	169	152	216	231	204
Total	**7,103**	**8,472**	**7,938**	**8,973**	**9,012**	**8,583**	**10,384**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Other Uses of Carbonates (Limestone and Dolomite Consumption)

Carbon dioxide emissions from other uses of carbonates, specifically limestone and dolomite consumption, were calculated using a Tier 2 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton carbonate for limestone and 0.47732 metric ton CO_2/metric ton carbonate for dolomite.[22] This methodology was used for limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization. Flux stone used during the production of iron and steel was deducted from the other uses of carbonates source category estimate and attributed to the iron and steel production source category estimate. Similarly, limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Consumption data for 1990 through 2022 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization (see Table 4-18) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995a through 2023b), preliminary data for 2022 from USGS Crushed Stone Commodity Expert (Willett 2023), American Iron and Steel Institute limestone and dolomite consumption data (AISI 2018 through 2021), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. In addition, the estimated values for limestone and dolomite consumption for flux stone used during the production of iron and steel were adjusted using emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) Subpart Q for the iron and steel sector to account for the impacts of the COVID-19 pandemic in 2020 and 2021. Iron and steel GHGRP process emissions data

[22] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

decreased by approximately 8 percent from 2021 to 2022 (EPA 2023). This adjustment method is consistent with the method used in Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use; therefore, data on consumption by end use for 1990 was estimated by applying the 1991 ratios of total limestone and dolomite consumption by end use to total 1990 limestone and dolomite consumption values. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 ratios of total limestone and dolomite use by end uses to the 1992 total values.

In 1991, the U.S. Bureau of Mines, now known as the USGS, began compiling production and end use information through surveys of crushed stone manufacturers. Manufacturers provided different levels of detail in survey responses, so information was divided into three categories: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified-reported" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "unspecified-estimated" production). Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

A large quantity of crushed stone was reported to the USGS under the category "unspecified uses." A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for "unspecified uses" was, therefore, allocated to all other reported end-uses according to each end-use's fraction of total consumption in that year.[23]

Table 4-18: Limestone and Dolomite Consumption from Other Uses of Carbonates (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	10,016	10,465	12,816	15,146	13,707	12,788	17,891
Dolomite	919	3,254	1,356	1,520	2,962	2,826	1,915
Total	**10,935**	**13,719**	**14,172**	**16,667**	**16,669**	**15,614**	**19,806**

Note: Totals may not sum due to independent rounding.

Ceramics Production

Carbon dioxide emissions from ceramics production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of clay consumed for emissive purposes by a carbonate content value of clay of 10 percent, limestone fraction of 85 percent and dolomite fraction of 15 percent, respectively, and by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton of limestone and 0.47732 metric ton CO_2/metric ton of dolomite.[24] To estimate annual process CO_2 emissions, EPA evaluated the end-uses of each type of clay published by USGS to identify the emissive end-uses that fall into the ceramics production subcategory. The emissive end-uses were organized into three groups: ceramics, glass, and floor & tile; refractories; and heavy clay products. The total limestone and dolomite consumption from the three emissive groupings for ceramics production for 1990 through 2022 (see Table 4-19) were obtained from USGS (Simmons 2024).

[23] This approach was recommended by USGS, the data collection agency.

[24] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-19: Limestone and Dolomite Consumption from Ceramics Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,444	1,569	797	762	758	764	776
Dolomite	255	277	141	135	134	135	137
Total	**1,699**	**1,846**	**938**	**897**	**892**	**899**	**913**

Note: Totals may not sum due to independent rounding.

Other Uses of Soda Ash

Carbon dioxide emissions from soda ash consumption were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Excluding glass manufacturing which is reported under Section 4.3 Glass Production (CRT Source Category 2A3), most soda ash is consumed in chemical production, with smaller amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed. The activity data for soda ash consumption for 1990 to 2022 (see Table 4-20) were obtained from the *U.S. Geological Survey (USGS) Minerals Yearbook for Soda Ash* (1994 through 2015b) and *USGS Mineral Industry Surveys for Soda Ash* (USGS 2017a, 2018, 2019, 2020b, 2021b, 2022a, 2023a). Soda ash consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-20: Other Uses of Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Soda Ash[a]	3,351	3,144	2,576	2,497	2,310	2,360	2,391

[a] Soda ash consumption is sales reported by producers which exclude imports. Historically, imported soda ash is less than 1 percent of the total U.S. consumption (Kostick 2012).

Non-Metallurgical Magnesia Production

Carbon dioxide emissions from non-metallurgical magnesia production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of magnesium ore extracted from the mine and processed at the facility by the carbonate content for magnesite or limestone, respectively, and by the emission factor for magnesite or limestone calcination, respectively: 0.52197 metric ton CO_2/metric ton carbonate for magnesite and 0.43971 metric ton CO_2/metric ton carbonate for limestone.[25] A USGS report on magnesite deposits at Gabbs, Nevada lists the carbonate content of magnesite as 98 percent magnesite and 1 percent limestone (USGS 1948). In the absence of other data, all magnesium ore extracted from the mine is assumed to be used for non-metallurgical magnesium production. Magnesium ore extracted from the mine and processed at the facility for non-metallurgical magnesia production for 2002 through 2022 (see Table 4-21) was obtained from the Nevada Department of Environmental Quality (McNeece 2023). This data was not available for 1990 through 2001. To address this gap in data availability and time-series consistency, carbonate consumption for 1990 through 2001 were estimated by multiplying the average ratio of magnesium ore consumption to production capacity for 2002 to 2004 by the production capacity of the facility in Nevada. Production capacity for 1990 through 2001 was obtained from the *USGS Minerals Yearbook for Magnesium Compounds* (USGS 1990 through 2002).

[25] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-21: Magnesite and Limestone Consumption from Non-Metallurgical Magnesia Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Magnesite	214	363	321	289	410	439	388
Limestone	2	4	3	3	4	4	4
Total	**216**	**367**	**325**	**292**	**414**	**443**	**392**

Note: Totals may not sum due to independent rounding.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied for non-metallurgical magnesia production to compare the magnesium ore consumption data to production capacity data for years where there was overlap. To address inconsistencies, adjustments were made, as described above.

Uncertainty

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. USGS contacts the mines (i.e., producers of various types of crushed stone) for annual sales data. Data on other carbonate consumption are not readily available. The producers report the annual quantity sold to various end-users and industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer/mines and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. EPA contacted the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with the limestone and dolomite consumption data compiled and published by USGS. During this discussion, the expert confirmed that EPA's range of uncertainty was still reasonable (Willett 2017). EPA assigned an uncertainty range of ±10 percent for limestone and dolomite consumption, based on expert judgement (Willett 2017). EPA assigned an uncertainty range of ±5 percent for soda ash consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed. EPA assigned an uncertainty range of ±3 percent for the CO_2 emission factors for limestone and dolomite consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

For emissions from ceramics production, data on clay consumption are collected by USGS through voluntary national surveys. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The accuracy of distribution by end use is also uncertain because this value is reported by the producer and not the end user. Uncertainty in the estimates also arises in part due to the variations in the carbonate content of the various clays used for the various types of ceramics. As discussed above, as no information is available on the carbonate content for each clay, fractions of limestone and dolomite consumed and a carbonate content for clay from the *2006 IPCC Guidelines* are used. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively.

For emissions from soda ash consumption, the primary source of uncertainty results from the fact that these emissions are dependent upon the type of processing employed by each end-use. Specific emission factors for each end-use are not available, so a Tier 1 default emission factor is used for all end-uses. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash. Additional uncertainty comes from the reported consumption and allocation of consumption within sectors that is collected on a quarterly basis by the USGS. Efforts have been made to categorize company sales within the correct end-use sector. EPA assigned an uncertainty range of ±2 percent for the CO_2 emission factor for soda ash consumption. The uncertainty range is derived from the default ranges for soda ash consumption for glass production in Volume 3, Chapter 2, Section 2.4.2.1 of the *2006 IPCC Guidelines* which is representative of soda ash consumption not associated with glass production, based on expert judgment (RTI 2023).

For non-metallurgical magnesia production, uncertainties arise due to variations in the chemical composition of the carbonates used in production of caustic-calcined magnesia production. As noted, minor quantities of other carbonates beyond limestone and magnesite are also used but unknown. These other carbonates are likely small and have a minimal impact on the derived emission factor. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-22.

A normal probability density function was assigned for all activity data, and a triangular probability density function was assigned for all emission factors (RTI 2023). Carbon dioxide emissions from other process uses of carbonates in 2022 were estimated to be between 9.2 and 12.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 15 percent above the emission estimate of 10.4 MMT CO_2 Eq.

Table 4-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Other Process Uses of Carbonates	CO_2	10.4	9.2	12.0	-12%	+15%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

For the current *Inventory*, emission estimates for new subcategories ceramics production and non-metallurgical magnesia production were incorporated across the entire time series. No other recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review the uncertainty ranges assigned to activity data. This planned improvement is currently planned as a medium-term improvement.

4.5 Ammonia Production (CRT Source Category 2B1)

Emissions of carbon dioxide (CO_2) occur during the production of synthetic ammonia (NH_3), primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions. This reporting category (2B1) includes emissions from the production of ammonia. Due to national circumstances, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. More information on this approach can be found in the Methodology section below.

Ammonia production requires a source of nitrogen (N) and hydrogen (H). Nitrogen is obtained from air through liquid air distillation or an oxidative process where air is burnt and the residual nitrogen is recovered. In the United States, the majority of ammonia is produced using a natural gas feedstock as the hydrogen source. One synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. In 2022, 16 companies operated 35 ammonia producing facilities in 16 states. Approximately 60 percent of domestic ammonia production capacity is concentrated in Louisiana, Oklahoma, and Texas (USGS 2023).

Synthetic ammonia production from natural gas feedstock consists of five principal process steps. The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and hydrogen (H_2) in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. In the shift conversion step, the CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air. Carbon dioxide is removed from the process gas by the shift conversion process, and the H_2 is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released from the solution.

The conversion process for conventional steam reforming of CH_4, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO_2 produced by the synthetic ammonia process are used as raw materials in the production of urea [$CO(NH_2)_2$], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO_2 that is captured during the ammonia production process and used to produce urea does not contribute to the CO_2 emission estimates for ammonia production

presented in this section. Instead, CO_2 emissions resulting from the consumption of urea are attributed to the urea consumption or urea application source category (under the assumption that the carbon stored in the urea during its manufacture is released into the environment during its consumption or application). Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6. Emissions of CO_2 resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in Section 4.6.

Emissions from fuel used for energy at ammonia plants are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The consumption of natural gas and petroleum coke as fossil fuel feedstocks for NH_3 production are adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. More information on this methodology is described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Total emissions of CO_2 from ammonia production in 2022 were 12.6 MMT CO_2 Eq. (12,610 kt) and are summarized in Table 4-23 and Table 4-24. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia. Since 1990, emissions from ammonia production have decreased by 12 percent. Emissions in 2022 increased by about 3 percent from the 2021 levels. One facility in Kansas produces ammonia from petroleum coke and began operations in 2000. All other facilities use natural gas as feedstock.

Emissions from ammonia production increased steadily from 2015 to 2018, due to the addition of new ammonia production facilities and new production units at existing facilities in 2016, 2017, and 2018. Agriculture continues to drive demand for nitrogen fertilizers, accounting for approximately 88 percent of domestic ammonia consumption (USGS 2023).

Table 4-23: CO_2 Emissions from Ammonia Production (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6

Table 4-24: CO_2 Emissions from Ammonia Production (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610

Methodology and Time-Series Consistency

Estimates of CO_2 emissions from the production of synthetic ammonia for 2010 through 2022 are estimated using a country-specific approach consistent with Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The methodology for 2010 to 2022 directly uses the process CO_2 emissions reported to subpart G of the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) (EPA 2018, EPA 2023). Estimates for 1990 to 2009 emissions are based on reported and calculated data on natural gas and petroleum coke feedstock used for ammonia production, consistent with IPCC Tier 2 methods and in accordance with the IPCC methodological decision tree and available data.

Emissions from fuel used for energy at ammonia plants are accounted for in the Energy chapter. This approach differs slightly from the *2006 IPCC Guidelines* which indicates that "in the case of ammonia production no distinction is made between fuel and feedstock emissions with all emissions accounted for in the IPPU Sector." Disaggregated data on fuel used for ammonia feedstock and fuel used for energy for ammonia production are not available in the United States. The Energy Information Administration (EIA), where energy use data are obtained for the *Inventory* (see the Energy chapter), does not provide data broken out by industrial category. EIA data are only available at the broad industry sector level. Furthermore, the GHGRP data used to estimate emissions are based on feedstock use and not fuel use. The method uses the same science informing the 2006 IPCC guidelines

and is consistent with avoiding double counting in the reporting of fuel use emissions under Energy and IPPU reporting. See more information in introduction to this Chapter.

Petroleum Coke Feedstock

Since 2000, one facility in the United States has produced ammonia using petroleum coke as a feedstock. For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated using CO_2 emissions reported by the facility to GHGRP (EPA 2018; EPA 2023).

For 2006 to 2009, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: quantity of petroleum coke feedstock reported by the facility (CVR 2008 through 2022); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and a stoichiometric CO_2/C factor of 44/12.

For 2000 to 2005, the quantity of petroleum coke feedstock was not available and was estimated by multiplying the average ratio of petroleum coke feedstock quantity to ammonia production quantity produced from petroleum coke from 2006 through 2010 by total ammonia production for 2000 to 2005 (ACC 2023). The years 2006 to 2010 were used to determine the average ratio of petroleum coke feedstock quantity to the ammonia quantity produced from petroleum coke because that period was deemed to better represent historic ammonia production from petroleum coke for the period from 2000 to 2005.

For 2000 to 2005, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: the average ratio of petroleum coke feedstock quantity to ammonia production quantity; total ammonia production quantity (ACC 2023); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and the stoichiometric ratio of CO_2 to C (44/12).

Natural Gas Feedstock

For 2017 through 2022, facilities directly reported to GHGRP the quantity of natural gas feedstock used for ammonia production along with the carbon content of the natural gas feedstock (EPA 2018; EPA 2023).

For 2010 through 2016, the quantity of natural gas feedstock was calculated using GHGRP process CO_2 emissions for 2010 through 2016, average molecular weight of the feedstock from 2017 through 2021, and average carbon content from 2017 through 2021. Data from years 2017 to 2021 were used to determine the average molecular weight and the average carbon content because that period better represents historic ammonia production from 2010 to 2016. Using all available data from 2017 to 2021 allowed for the maximum number of data points available at the time of adopting this methodology to ensure that the average was representative. The averages were not updated using later data to exclude any new facilities that might not be representative of facilities that were operating during the earlier years of the GHGRP.

For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the CO_2 emissions reported to the GHGRP (EPA 2018; EPA 2023) and subtracting the CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock as determined in the Petroleum Coke Feedstock section above.

For 1990 to 2009, the quantity of natural gas feedstock was not available and was estimated by multiplying the average ratio of natural gas feedstock quantity to ammonia production quantity from 2010 through 2014 by total ammonia production for each year for 1990 to 2009 (ACC 2023). The years 2010 to 2014 were used to determine the average ratio of natural gas feedstock quantity to ammonia production because that period better represents

historic ammonia production from 1990 to 2009.[26] For 1990 to 2009, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the natural gas feedstock quantity as determined above and the *Inventory* CO_2 emissions factor and heating content value for natural gas (consistent with values used in the Energy chapter).

Urea Production Adjustments

Emissions of CO_2 from ammonia production from both feedstocks and for all years from 1990 to 2022 were adjusted to account for the use of some CO_2 emissions resulting from ammonia production as a raw material in the production of urea. The CO_2 emissions reported for ammonia production are reduced by a factor of 0.733, which corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of ammonia (NH_3) and CO_2 to urea (IPCC 2006; EFMA 2000), and multiplied by total annual domestic urea production.

All synthetic ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at the one facility located in Kansas.

Table 4-25: Total Ammonia Production, Total Urea Production, and Recovered CO_2 Consumed for Urea Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Total Ammonia Production	15,425	10,143	16,010	16,410	17,020	15,420	16,800
Total Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Recovered CO_2 Consumed for Urea Production	5,463	3,865	7,847	8,360	8,433	7,715	8,266

Total ammonia production, total urea production, and recovered CO_2 consumed for urea production are shown in Table 4-25. Total ammonia production data for 2011 through 2022 were obtained from American Chemistry Council (ACC 2023). For years 1990 through 2011, ammonia production data were obtained from the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Data on facility-level process emissions for 2010 through 2022 and data on natural gas feedstock used and carbon content of the natural gas feedstock starting in 2017 were obtained from GHGRP (EPA 2018; EPA 2023). Natural gas and petroleum coke heating values come from national-level data (EIA 2023), and natural gas and petroleum coke carbon contents are the same as used in the Energy chapter calculations.

Data on urea production for 2010 through 2022 were obtained from GHGRP (EPA 2018, EPA 2023). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2010 and 2011). Urea production data for 1990 through 2008 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 1994-2009). The U.S. Census Bureau ceased collection of urea production statistics in 2011.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ammonia production spliced activity data from different sources: U. S. Census Bureau data for 1990 through 2010, ACC data beginning in 2011, and GHGRP data beginning in 2010 and 2017. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

[26] The number of facilities reporting to GHGRP has increased since 2010: 22 facilities reported from 2010 to 2012; 23 from 2013 to 2015; 26 in 2016; 28 in 2017 and 29 from 2018 to 2022. Using data from 2010 to 2014 excludes the newer facilities that might not be representative of facilities in earlier years.

Uncertainty

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainty in the back calculation of natural gas feedstock used for 1990 through 2009 also exists. Using the average ratio of natural gas feedstock quantity to ammonia production, determined using GHGRP data from 2010 to 2014, does not account for efficiency gains in ammonia production since 1990 (e.g., potential decreases in gas usage per ton of ammonia, manufacturing shift from steam-driven turbines to electrical-drive turbines). Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at co-located plants from the same natural gas raw material. The uncertainty of the total urea production activity data, based on USGS *Minerals Yearbook: Nitrogen* data, is a function of the reliability of reported production data and is influenced by the completeness of the survey responses. EPA assigned an uncertainty range of ±5 percent for ammonia production and a range of ±2 percent for urea production, natural gas feedstock quantity, petroleum coke feedstock quantity, and carbon content of natural gas feedstock, and using the suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgement, a normal probability density function was assigned for all variables.

Recovery of CO_2 from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO_2 emissions from ammonia production, as data concerning the disposition of recovered CO_2 are not available. Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere; however, for reporting purposes, CO_2 consumption for urea production is provided in this chapter.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-26. Carbon dioxide emissions from ammonia production in 2022 were estimated to be between 12.2 and 13.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 12.6 MMT CO_2 Eq.

Table 4-26: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	12.6	12.2	13.1	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied to ammonia production emission estimates consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to ammonia facilities can be found

under Subpart G (Ammonia Production) of the regulation (40 CFR Part 98).[27] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[28] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

More details on the greenhouse gas calculation, monitoring, and QA/QC methods applicable to reporting of urea produced at ammonia production facilities can be found under Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Recalculations

For 2021, the urea consumption value was changed from a rounded value to a more precise unrounded value. As a result, recalculations were performed for emissions from ammonia for 2021. Compared to the previous *Inventory*, total CO_2 emissions from the production of ammonia production (from natural gas and petroleum coke feedstocks) decreased by less than 1 percent (15 kt) in 2021.

Planned Improvements

Currently the *Inventory* does not separately track fuel energy use for ammonia production. To be more consistent with *2006 IPCC Guidelines*, EPA is considering whether to include natural gas fuel use as part of ammonia production emissions as a future improvement. The data are still being evaluated as part of EPA's efforts to disaggregate other industrial sector categories' energy use in the Energy chapter of the *Inventory*. If possible, this will be incorporated in future *Inventory* reports. If incorporated, the fuel energy use and emissions will be removed from current reporting under Energy to avoid double counting.

4.6 Urea Consumption for Non-Agricultural Purposes (CRT Source Category 2B10)

Urea is produced using ammonia (NH_3) and carbon dioxide (CO_2) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. There were 35 plants producing ammonia in the United States in 2022, with two additional plants sitting idle for the entire year (USGS 2023b).

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

This section accounts for CO_2 emissions associated with urea consumed exclusively for non-agricultural purposes. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from urea consumption for non-agricultural purposes. Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 of the Agriculture chapter.

[27] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[28] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The industrial applications of urea include its use in adhesives, binders, sealants, resins, fillers, analytical reagents, catalysts, intermediates, solvents, dyestuffs, fragrances, deodorizers, flavoring agents, humectants and dehydrating agents, formulation components, monomers, paint and coating additives, photosensitive agents, and surface treatments agents. In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2022 were estimated to be 7.1 MMT CO_2 Eq. (7,053 kt) and are summarized in Table 4-27 and Table 4-28. Net CO_2 emissions from urea consumption for non-agricultural purposes have increased by approximately 86 percent from 1990 to 2022 and increased by approximately 7 percent from 2021 to 2022.

Table 4-27: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3.8	3.7	6.1	6.2	5.8	6.6	7.1

Table 4-28: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3,784	3,653	6,113	6,150	5,805	6,600	7,053

Methodology and Time-Series Consistency

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated using a country-specific method consistent with the Tier 1 method used to estimate emissions from ammonia production in the *2006 IPCC Guidelines* which states that the "CO_2 recovered [from ammonia production] for downstream use can be estimated from the quantity of urea produced where CO_2 is estimated by multiplying urea production by 44/60, the stoichiometric ratio of CO_2 to urea" (IPCC 2006). The amount of urea consumed in the United States for non-agricultural purposes is multiplied by a factor representing the amount of CO_2 used as a raw material to produce the urea. This method is based on the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The amount of urea consumed for non-agricultural purposes in the United States is estimated by deducting the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Agriculture chapter (see Table 5-25), from the total domestic supply of urea as reported in Table 4-29. The domestic supply of urea is estimated based on the amount of urea produced plus urea imports and minus urea exports. A factor of 0.733 tons of CO_2 per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO_2 emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO_2 per ton of urea emission factor is based on the stoichiometry of carbon in urea. This corresponds to a stoichiometric ratio of CO_2 to urea of 44/60, assuming complete conversion of carbon in urea to CO_2 (IPCC 2006; EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009a). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Urea production data for 2011 through 2022 were obtained from GHGRP (EPA 2018; EPA 2023a; EPA 2023b).

Urea import data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea import data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea import data for 2011 and 2012 were taken from U.S. Fertilizer Import/Exports from the United States Department of Agriculture (USDA) Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012. Urea import data for the previous years were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for

1997 through 2010 (U.S. Census Bureau 2001 through 2011), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-29).

Urea export data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea export data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea export data for 1990 through 2012 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012.

Table 4-29: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Urea Applied as Fertilizer	3,296	4,779	6,732	6,865	6,998	7,131	7,265
Urea Imports	1,860	5,026	5,110	4,410	4,190	5,880	5,880
Urea Exports	854	536	743	559	777	270	270
Urea Consumed for Non-Agricultural Purposes	5,160	4,981	8,335	8,386	7,915	9,000	9,617

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for urea consumption for non-agricultural purposes spliced activity data from different sources: USGS data for 1990 through 2008, U. S. Census Bureau data for 2009 and 2010, and GHGRP data beginning in 2011. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

There is limited publicly available data on the quantities of urea produced and consumed for non-agricultural purposes. Therefore, the amount of urea used for non-agricultural purposes is estimated based on a balance that relies on estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer. EPA uses an uncertainty range of ±10 percent for urea production and ±5 percent for urea imports and urea exports, consistent with the ranges for activity data that are not obtained directly from plants, and using this suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for all activity data. The primary uncertainties associated with this source category are associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-30. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes during 2022 were estimated to be between 6.8 and 7.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 7.1 MMT CO_2 Eq.

Table 4-30: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	7.1	6.8	7.3	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea production occurring at ammonia facilities can be found under Subpart G (Ammonia Manufacturing) of the regulation (40 CFR Part 98).[29] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[30] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported urea production data against external datasets including the USGS *Minerals Yearbook* data. The comparison shows consistent trends in urea production over time.

Recalculations Discussion

Based on updated quantities of urea applied for agricultural uses for 2017 through 2021, updated urea imports from USGS for 2021, and updated urea exports from USGS for 2021, recalculations were performed for 2017 through 2021. Compared to the previous *Inventory*, CO_2 emissions from urea consumption for non-agricultural purposes increased by less than 1 percent for 2017 (46 kt CO_2) and 2018 (2 kt CO_2), decreased by less than 1 percent for 2019 (4 kt CO_2) and 2020 (10 kt CO_2) and increased by 32 percent for 2021 (1,611 kt CO_2).

Planned Improvements

At this time, there are no specific planned improvements for estimating CO_2 emissions from urea consumption for non-agricultural purposes.

[29] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[30] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

4.7 Nitric Acid Production (CRT Source Category 2B2)

Nitrous oxide (N_2O) is emitted during the production of nitric acid (HNO_3), an inorganic compound used primarily to make synthetic commercial fertilizers. Nitric acid is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. This reporting category (2B2) includes emissions from production of nitric acid. Emissions from fuels consumed for energy purposes during the production of nitric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

There are two types of nitric acid: weak nitric acid and high-strength nitric acid. The weak nitric acid production method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength nitric acid (90 percent or greater nitric acid) can be produced by two methods: (1) through the dehydration, bleaching, condensing, and absorption of the weak nitric acid or (2) through the oxidation of ammonia into nitric oxide, which is oxidized and cooled into dinitrogen tetroxide and then pressurized and oxidized into high-strength nitric acid. Most U.S. plants were built between 1960 and 2000. As of 2022, there were 31 active nitric acid production plants that produce weak nitric acid in the United States (EPA 2023). One plant produces both weak and high-strength nitric acid (EPA 2010).

The basic process technology for producing nitric acid has not changed significantly over time. During this process, N_2O is formed as a byproduct and released from reactor vents into the atmosphere.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2$$

Currently, the nitric acid industry in the United States controls emissions of NO and NO_2 (i.e., NO_x), using a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. Five nitric acid plants had NSCR systems installed between 1964 and 1977, over half due to the finalization of the Nitric Acid Plant New Source Performance Standards (NSPS) which went into effect in 1971. Four additional nitric acid plants had NSCR systems installed between 2016 and 2018, as a result of EPA Consent Decrees to control NO_X emissions more effectively. NSCR systems are used in approximately one-third of the weak acid production plants. For N_2O abatement, U.S. facilities are using both tertiary (i.e., NSCR and SCR) and secondary controls (i.e., catalysts added to the ammonia reactor to lessen potential N_2O production).

Emissions from the production of nitric acid are generally directly proportional to the annual amount of nitric acid produced because emissions are calculated as the product of the total annual production and plant-specific emission factors. There are a few instances, however, where that relationship has not been directly proportional. For example, in 2015 and 2019, nitric acid production decreased and emissions increased compared to the respective preceding years; in 2016, nitric acid production increased and emissions decreased compared to 2015. N_2O emissions for those years are calculated based on data from the GHGRP as discussed in the Methodology section below. According to data from plants reporting to GHGRP, plant-specific operations can affect the emission factor used, including: (1) site-specific fluctuations in ambient temperature and humidity, (2) catalyst age and condition, (3) process changes, such as fluctuations in process pressure or temperature and replacing the ammonia catalyst, (4) the addition, removal, maintenance, and utilization of abatement technologies, and (5) the number of nitric acid trains, which are reaction vessels where ammonia is oxidized to form nitric acid. Changes in those operating conditions for the years in question (2015, 2016, and 2019) caused changes in emission factors, which resulted in emissions changing disproportionally to production in those years.

Nitrous oxide emissions from this source were estimated to be 8.6 MMT CO_2 Eq. (33 kt of N_2O) in 2022 and are summarized in Table 4-31 and Table 4-32. Emissions from nitric acid production have decreased by 20 percent since 1990, while production has increased by 9 percent over the same time period (see Table 4-31 and Table

4-32). Emissions have decreased by 33 percent since 1997, the highest year of production in the time series. From 2021 to 2022, nitric acid production increased by 1 percent, while overall emissions from nitric acid production increased by 9.4 percent from 2021 to 2022.

Table 4-31: N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6

Table 4-32: N_2O Emissions from Nitric Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	41	38	32	34	31	30	33

Methodology and Time-Series Consistency

Emissions of N_2O from nitric acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions based on GHGRP data. For 1990 through 2009, a Tier 2 method was used to estimate emissions from nitric acid production based on U.S. Census Bureau data.

2010 through 2022

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2022 by aggregating reported facility-level data (EPA 2018; EPA 2023).[31]

Since 2010, in the United States, all nitric acid facilities that produce weak nitric acid (30 to 70 percent) have been required to report annual greenhouse gas emissions data to EPA as per the requirements of the GHGRP (Subpart V). Beginning with 2018, the rule was changed to include facilities that produce nitric acid of any strength. The only facility that produces high-strength nitric acid also produces weak nitric acid. All N_2O emissions from nitric acid production originate from the production of weak nitric acid.

Process emissions and nitric acid production reported to the GHGRP provide complete estimates of greenhouse gas emissions for the United States because there are no reporting thresholds. While facilities are allowed to stop reporting to the GHGRP if the total reported emissions from nitric acid production are less than 25,000 metric tons CO_2 Eq. per year for five consecutive years or less than 15,000 metric tons CO_2 Eq. per year for three consecutive years, no facilities have stopped reporting as a result of these provisions.[32] All nitric acid facilities are required to either calculate process N_2O emissions using a site-specific emission factor that is the average of the emission factor determined through annual performance tests for each nitric acid train under typical operating conditions or directly measure process N_2O emissions using monitoring equipment.[33]

Emissions from facilities vary from year to year, depending on the amount of nitric acid produced with and without abatement technologies and other conditions affecting the site-specific emission factor. To maintain consistency

[31] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology were aggregated from the GHGRP facility-level data for 2010 to 2022 (i.e., percent production with and without abatement).

[32] See 40 CFR 98.2(i)(1) and 40 CFR 98.2(i)(2) for more information about these provisions.

[33] Facilities must use standard methods - either EPA Method 320 or ASTM D6348-03 for annual performance tests—and must follow associated QA/QC procedures consistent with category-specific QC of direct emission measurements during these performance tests.

across the time series and with the rounding approaches taken by other data sets, GHGRP nitric acid data are rounded and are shown in Table 4-33.

1990 through 2009

Using GHGRP data for 2010, country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors). The following 2010 emission factors were derived for production with abatement and without abatement: 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.99 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Country-specific weighted emission factors were derived by weighting these emission factors by percent production with abatement and without abatement over time periods 1990 through 2008 and 2009. These weighted emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the availability of GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted emission factor is included for 2009 due to data availability for that year.

EPA verified the installation dates of N_2O abatement technologies for all facilities based on GHGRP facility-level information and confirmed that all abatement technologies were accounted for in the derived emission factors (Icenhour 2020). Due to the lack of information on abatement equipment utilization, it is assumed that once abatement technology was installed in facilities, the equipment was consistently operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N_2O emission factors were used in conjunction with annual production to estimate N_2O emissions for 1990 through 2009, using the following equations:

Equation 4-4: *2006 IPCC Guidelines* Tier 3: N_2O Emissions From Nitric Acid Production (Equation 3.6)

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = \left[\left(\%P_{c,i} \times EF_c\right) + \left(\%P_{unc,i} \times EF_{unc}\right)\right]$$

where,

E_i	=	Annual N_2O Emissions for year i (kg/yr)
P_i	=	Annual nitric acid production for year i (metric tons HNO_3)
$EF_{weighted,i}$	=	Weighted N_2O emission factor for year i (kg N_2O/metric ton HNO_3)
$\%P_{c,i}$	=	Percent national production of HNO_3 with N_2O abatement technology (%)
EF_c	=	N_2O emission factor, with abatement technology (kg N_2O/metric ton HNO_3)
$\%P_{unc,i}$	=	Percent national production of HNO_3 without N_2O abatement technology (%)
EF_{unc}	=	N_2O emission factor, without abatement technology (kg N_2O/metric ton HNO_3)
i	=	year from 1990 through 2009

- For 2009: Weighted N_2O emission factor = 5.46 kg N_2O/metric ton HNO_3.
- For 1990 through 2008: Weighted N_2O emission factor = 5.66 kg N_2O/metric ton HNO_3.

Nitric acid production data for the United States for 1990 through 2009 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2008, 2009, 2010a, 2010b) (see Table 4-33). EPA used GHGRP facility-level information to verify that all reported N_2O abatement equipment were incorporated into the estimation of N_2O emissions from nitric acid production over the full time series (EPA 2021).

Table 4-33: Nitric Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	7,200	6,710	8,210	8,080	7,970	7,800	7,860

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for nitric acid production spliced activity data from two different sources: U.S. Census Bureau production data for 1990 through 2009 and GHGRP production data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with the parameters used to estimate N_2O emissions includes the share of U.S. nitric acid production attributable to each emission abatement technology (i.e., utilization) over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type. While some information has been obtained through outreach with industry associations, limited information is available over the time series (especially prior to 2010) for a variety of facility level variables, including plant-specific production levels, plant production technology (e.g., low or high pressure, etc.), and abatement technology destruction and removal efficiency rates. Production data prior to 2010 were obtained from National Census Bureau, which does not provide uncertainty estimates with their data. Facilities reporting to EPA's GHGRP must measure production using equipment and practices used for accounting purposes. While emissions are often directly proportional to production, the emission factor for individual facilities can vary significantly from year to year due to site-specific fluctuations in ambient temperature and humidity, catalyst age and condition, nitric acid production process changes, the addition or removal of abatement technologies, and the number of nitric acid trains at the facility. At this time, EPA does not estimate uncertainty of the aggregated facility-level information. As noted in the QA/QC and verification section below, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. The annual production reported by each nitric acid facility under EPA's GHGRP and then aggregated to estimate national N_2O emissions is assumed to have low uncertainty. EPA assigned an uncertainty range of ±5 percent for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for nitric acid production, and using this suggested uncertainty provided in section 3.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for facility-reported N_2O emissions and nitric acid production.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-34. Nitrous oxide emissions from nitric acid production were estimated to be between 8.2 and 9.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2022 emissions estimate of 8.6 MMT CO_2 Eq.

Table 4-34: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	8.6	8.2	9.0	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to nitric acid facilities can be found under Subpart V: Nitric Acid Production of the GHGRP regulation (40 CFR Part 98). [34]

The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the Subpart (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred (EPA 2015). [35] EPA's review of observed trends noted that while emissions have generally mirrored production, in 2015 and 2019 nitric acid production decreased compared to the previous year and emissions increased. While review is ongoing, based on feedback from the verification process to date, these changes are due to facility-specific changes (e.g., in the nitric production process and management of abatement equipment).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

Pending resources, EPA is considering a near-term improvement to both review and refine quantitative uncertainty estimates and the associated qualitative discussion.

4.8 Adipic Acid Production (CRT Source Category 2B3)

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. This reporting category (2B3) includes emissions from the production of adipic acid. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Adipic acid is produced through a two-stage process during which nitrous oxide (N_2O) is generated in the second stage. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce

[34] See Subpart V monitoring and reporting regulation http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[35] See GHGRP Verification Factsheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

adipic acid. Nitrous oxide is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). The second stage is represented by the following chemical reaction:

$$(CH_2)_5CO(cyclohexanone) + (CH_2)_5CHOH(cyclohexanol) + wHNO_3 \rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + xN_2O + yH_2O$$

Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). In 2022, thermal reduction was applied as an N_2O abatement measure at one adipic acid facility (EPA 2023).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers, with the United States accounting for the largest share of global adipic acid production capacity in recent years. In 2022, the United States had two companies with a total of two adipic acid production facilities (one in Texas and one in Florida), following the ceased operations of a third major production facility at the end of 2015 (EPA 2023).

Commercially, adipic acid is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6; 9 percent is used in the production of polyester polyols; 4 percent is used in the production of plasticizers; and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a "tangy" flavor (Thiemens and Trogler 1991).

Compared to 1990, national adipic acid production in 2022 has increased by 3 percent to approximately 780,000 metric tons (ACC 2023). Nitrous oxide emissions from adipic acid production were estimated to be 2.1 MMT CO_2 Eq. (8 kt N_2O) in 2022 and are summarized in Table 4-35 and Table 4-36. Over the period 1990 through 2022, facilities have reduced emissions by 84.5 percent due to the widespread installation of pollution control measures in the late 1990s. The main reason for the 68 percent decrease in N_2O emissions from adipic acid production between 2021 and 2022 is increased utilization of N_2O abatement equipment at one adipic acid production facility.

EPA reviewed GHGRP facility reported information on the date of abatement technology installation in order to better reflect trends and changes in emissions abatement within the industry across the time series. The facility using the facility-specific emission factor developed through annual performance testing has reported no installation and no utilization of N_2O abatement technology. The facility using direct measurement of N_2O emissions has reported the use of thermal reduction as an N_2O abatement technology; the first unit began operation in 1980, and the second unit began operation in 2023 (Ard 2024; Ascend 2023).

Significant changes in the amount of time that the N_2O abatement device at one facility was in operation has been the main cause of fluctuating emissions in recent years. These fluctuations are most evident for years where trends in emissions and adipic acid production were not directly proportional: (1) between 2016 and 2017, (2) between 2017 and 2018, (3) between 2019 and 2020, (4) between 2020 and 2021, and (5) between 2021 and 2022. As noted above, changes in control measures and abatement technologies at adipic acid production facilities, including maintenance of equipment, can result in annual emission fluctuations. Little additional information is available on drivers of trends, and the amount of adipic acid produced is not reported under EPA's GHGRP.

Table 4-35: N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1

Table 4-36: N_2O Emissions from Adipic Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	51	24	35	18	28	25	8

Methodology and Time-Series Consistency

Emissions of N_2O from adipic acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions. For 1990 through 2009, emissions are estimated using both Tier 2 and Tier 3 methods. Due to confidential business information (CBI), plant names are not provided in this section; therefore, the four adipic acid-producing facilities that have operated over the time series will be referred to as Plants 1 through 4. As noted above, one currently operating facility uses thermal reduction as an N_2O abatement technology.

2010 through 2022

All emission estimates for 2010 through 2022 were obtained through analysis of GHGRP data (EPA 2010 through 2023). Facility-level greenhouse gas emissions data were obtained from EPA's GHGRP for the years 2010 through 2022 (EPA 2010 through 2023) and aggregated to national N_2O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to either calculate N_2O emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or directly measure N_2O emissions using monitoring equipment.[36]

1990 through 2009

For years 1990 through 2009, which were prior to EPA's GHGRP reporting, for both Plants 1 and 2, emission estimates were obtained directly from the plant engineers and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered CBI and hence are not published (Desai 2010, 2011). These estimates were based on continuous process monitoring equipment installed at the two facilities.

For Plant 4, 1990 through 2009 N_2O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines*:

Equation 4-5: *2006 IPCC Guidelines* Tier 2: N_2O Emissions From Adipic Acid Production (Equation 3.8)

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

E_{aa}	=	N_2O emissions from adipic acid production, metric tons
Q_{aa}	=	Quantity of adipic acid produced, metric tons
EF_{aa}	=	Emission factor, metric ton N_2O/metric ton adipic acid produced
DF	=	N_2O destruction factor
UF	=	Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N_2O emitted per unit of adipic acid produced), which has been estimated to be approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). The "N_2O destruction factor" in the equation represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the

[36] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance testing, and must follow associated QA/QC procedures during these performance tests consistent with category-specific QC of direct emission measurements.

abatement equipment operates during the annual production period. Plant-specific production data for Plant 4 were obtained across the time series through personal communications (Desai 2010, 2011). The plant-specific production data were then used for calculating emissions as described above.

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant (Desai 2010, 2011). For 1990 through 2004, emissions were estimated using plant-specific production data and the IPCC factors as described above for Plant 4. Plant-level adipic acid production for 1990 through 2003 was estimated by allocating national adipic acid production data to the plant level using the ratio of known plant capacity to total national capacity for all U.S. plants (ACC 2023; CMR 2001, 1998; CW 1999; C&EN 1992 through 1995). For 2004, actual plant production data were obtained and used for emission calculations (CW 2005).

Plant capacities for 1990 through 1994 were obtained from *Chemical & Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for the year 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 2003, the plant capacities for three plants were held constant at year 2000 capacities. Plant capacity for 1999 to 2003 for the one remaining plant was kept the same as 1998.

National adipic acid production data (see Table 4-37) from 1990 through 2022 were obtained from the American Chemistry Council (ACC 2023).

Table 4-37: Adipic Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	755	865	825	810	710	760	780

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for adipic acid production spliced activity data from multiple sources: plant-specific emissions data and publicly available plant capacity data for 1990 through 2009 and GHGRP emission data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with N_2O emission estimates includes the methods used by companies to monitor and estimate emissions. While some information has been obtained through outreach with facilities, limited information is available over the time series on these methods, abatement technology destruction and removal efficiency rates, and plant-specific production levels. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-38. Nitrous oxide emissions from adipic acid production for 2022 were estimated to be between 2.0 and 2.2 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 4 percent below to 4 percent above the 2022 emission estimate of 2.1 MMT CO_2 Eq.

Table 4-38: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	2.1	2.0	2.2	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to adipic acid facilities can be found under Subpart E (Adipic Acid Production) of the GHGRP regulation (40 CFR Part 98).[37] The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[38] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year comparisons of reported data.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA has no specific planned improvements related to adipic acid.

4.9 Caprolactam, Glyoxal and Glyoxylic Acid Production (CRT Source Category 2B4)

This reporting category (2B4) includes emissions from the production of caprolactam, glyoxal (ethanedial), and glyoxylic acid. Emissions from fuels consumed for energy purposes during the production of caprolactam, glyoxal,

[37] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[38] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

and glyoxylic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Caprolactam

Caprolactam ($C_6H_{11}NO$) is a colorless monomer produced for nylon-6 fibers and plastics. A substantial proportion of the fiber is used in carpet manufacturing. Most commercial processes used for the manufacture of caprolactam begin with benzene, but toluene can also be used. The production of caprolactam can give rise to emissions of nitrous oxide (N_2O).

During the production of caprolactam, emissions of N_2O can occur from the ammonia oxidation step, emissions of carbon dioxide (CO_2) from the ammonium carbonate step, emissions of sulfur dioxide (SO_2) from the ammonium bisulfite step, and emissions of non-methane volatile organic compounds (NMVOCs). Emissions of CO_2, SO_2 and NMVOCs from the conventional process are unlikely to be significant in well-managed plants. Modified caprolactam production processes are primarily concerned with elimination of the high volumes of ammonium sulfate that are produced as a byproduct of the conventional process (IPCC 2006).

In the most commonly used process where caprolactam is produced from benzene, benzene is hydrogenated to cyclohexane which is then oxidized to produce cyclohexanone ($C_6H_{10}O$). The classical route (Raschig process) and basic reaction equations for production of caprolactam from cyclohexanone are (IPCC 2006):

$$Oxidation\ of\ NH_3\ to \frac{NO}{NO_2}$$

$$\downarrow$$

$$NH_3\ reacted\ with \frac{CO_2}{H_2O} to\ yield\ ammonium\ carbonate\ (NH_4)_2CO_3$$

$$\downarrow$$

$$(NH_4)_2CO_3\ reacted\ with \frac{NO}{NO_2} (from\ NH_3\ oxidation) to\ yield\ ammonium\ nitrite\ (NH_4NO_2)$$

$$\downarrow$$

$$NH_3\ reacted\ with \frac{SO_2}{H_2O} to\ yield\ ammonium\ bisulphite\ (NH_4HSO_3)$$

$$\downarrow$$

$$NH_4NO_2\ and\ (NH_4HSO_3) reacted\ to\ yield\ hydroxylamine\ disulphonate\ (NOH(SO_3NH_4)_2)$$

$$\downarrow$$

$$(NOH(SO_3NH_4)_2)\ hydrolised\ to\ yield\ hydroxylamine\ sulphate\ ((NH_2OH)_2.H_2SO_4)\ and$$

$$ammonium\ sulphate\ ((NH_4)_2SO_4)$$

$$\downarrow$$

$$Cylohexanone\ reaction:$$

$$C_6H_{10}O\ + \frac{1}{2}(NH_2OH)_2.H_2SO_4 (+NH_3\ and\ H_2SO_4) \rightarrow C_6H_{10}NOH\ + (NH_4)_2SO_4\ + H_2O$$

$$\downarrow$$

$$Beckmann\ rearrangement:$$

$$C_6H_{10}NOH\ \ (+H_2SO_4\ and\ SO_2) \rightarrow C_6H_{11}NO.H_2SO_4\ (+4NH_3\ and\ H_2O) \rightarrow C_6H_{11}NO\ + 2(NH4)_2SO_4$$

In 2004, three facilities produced caprolactam in the United States (ICIS 2004). Another facility, Evergreen Recycling, was in operation from 2000 to 2001 (ICIS 2004; Textile World 2000) and from 2007 through 2015 (Shaw

2015). Caprolactam production at Fibrant LLC (formerly DSM Chemicals) in Georgia ceased in 2018 (Cline 2019). As of 2022, two companies in the United States produced caprolactam at two facilities: AdvanSix (formerly Honeywell) in Virginia (AdvanSix 2023) and BASF in Texas (BASF 2023).

Nitrous oxide emissions from caprolactam production in the United States were estimated to be 1.3 MMT CO_2 Eq. (5 kt N_2O) in 2022 and are summarized in Table 4-39 and Table 4-40. National emissions from caprolactam production decreased by approximately 10.5 percent over the period of 1990 through 2022. Emissions in 2022 increased by approximately 9.8 percent from the 2021 levels. This annual increase returned caprolactam production to levels consistent with 2017 before the COVID-19 pandemic.

Table 4-39: N_2O Emissions from Caprolactam Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3

Table 4-40: N_2O Emissions from Caprolactam Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	6	7	5	5	4	5	5

Glyoxal

Glyoxal is mainly used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectant, gelatin hardening agent, textile finishing agent (permanent-press cotton, rayon fabrics), and wet-resistance additive (paper coatings) (IPCC 2006). It is also used for enhanced oil-recovery. It is produced from oxidation of acetaldehyde with concentrated nitric acid, or from the catalytic oxidation of ethylene glycol, and N_2O is emitted in the process of oxidation of acetaldehyde.

Glyoxal (ethanedial) ($C_2H_2O_2$) is produced from oxidation of acetaldehyde (ethanal) (C_2H_4O) with concentrated nitric acid (HNO_3). Glyoxal can also be produced from catalytic oxidation of ethylene glycol (ethanediol) (CH_2OHCH_2OH).

Glyoxylic Acid

Glyoxylic acid is produced by nitric acid oxidation of glyoxal. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals, and pharmaceutical intermediates (IPCC 2006).

Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. EPA does not currently estimate the emissions associated with the production of glyoxal and glyoxylic acid because activity data are not available. See Annex 5 for more information.

Methodology and Time-Series Consistency

Emissions of N_2O from the production of caprolactam are calculated using the Tier 1 methodology from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-6: *2006 IPCC Guidelines* Tier 1: N_2O Emissions From Caprolactam Production (Equation 3.9)

$$E_{N_2O} = EF \times CP$$

where,

E_{N_2O} = Annual N_2O Emissions (kg)

EF = N_2O emission factor (default) (kg N_2O/metric ton caprolactam produced)

CP = Caprolactam production (metric tons)

During the caprolactam production process, N_2O is generated as a byproduct of the high temperature catalytic oxidation of ammonia (NH_3), which is the first reaction in the series of reactions to produce caprolactam. The amount of N_2O emissions can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 111.1 metric tons of caprolactam are required to generate one metric ton of N_2O, resulting in an emission factor of 9.0 kg N_2O per metric ton of caprolactam (IPCC 2006). When applying the Tier 1 method, the *2006 IPCC Guidelines* state that it is good practice to assume that there is no abatement of N_2O emissions and to use the highest default emission factor available in the guidelines. In addition, EPA did not find support for the use of secondary catalysts to reduce N_2O emissions, such as those employed at nitric acid plants.

The activity data for caprolactam production (see Table 4-41) from 1990 to 2022 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). EPA will continue to analyze and assess alternative sources of production data as a quality control measure.

Table 4-41: Caprolactam Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	626	795	530	515	480	510	560

Carbon dioxide and methane (CH_4) emissions may also occur from the production of caprolactam, but currently the IPCC does not have methodologies for calculating these emissions associated with caprolactam production.

Methodological approaches, consistent with the *2006 IPCC Guidelines*, have been applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Estimation of emissions of N_2O from caprolactam production can be treated as analogous to estimation of emissions of N_2O from nitric acid production. Both production processes involve an initial step of NH_3 oxidation, which is the source of N_2O formation and emissions (IPCC 2006). Therefore, uncertainties for the default emission factor values in the *2006 IPCC Guidelines* are an estimate based on default values for nitric acid plants. In general, default emission factors for gaseous substances have higher uncertainties because mass values for gaseous substances are influenced by temperature and pressure variations and gases are more easily lost through process leaks. The default values for caprolactam production have a relatively high level of uncertainty due to the limited information available (IPCC 2006). EPA assigned uncertainty bounds of ±5 percent for caprolactam production, based on expert judgment. EPA assigned an uncertainty range of ±40 percent for the N_2O emission factor, and using this suggested uncertainty provided in Section 3.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probably density function was assigned for the emission factor.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Nitrous oxide emissions from caprolactam, glyoxal and glyoxylic acid production for 2022 were estimated to be between 0.9 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 31 percent below to 31 percent above the 2022 emission estimate of 1.3 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Caprolactam Production	N_2O	1.3	0.9	1.8	-31%	+31%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2020 and 2021 to reflect updated caprolactam production data from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). Compared to the previous *Inventory*, annual N_2O emissions decreased by 2 percent in 2020 and 2021, with a decrease of 0.02 MMT CO_2 Eq. in 2020 and 2021.

Planned Improvements

Pending resources, EPA will research other available datasets for caprolactam production and industry trends, including facility-level data. EPA continues to research available activity data and emissions associated with the production of glyoxal and glyoxylic acid. Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. See Annex 5 for more information. This planned improvement is subject to data availability and will be implemented in the medium- to long-term.

4.10 Carbide Production and Consumption (CRT Source Category 2B5 & 2B10)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used for industrial abrasive, metallurgical, and other non-abrasive applications in the United States, and CO_2 is emitted from the consumption of SiC. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the industrial end-use sector reported under the Energy chapter. Additionally, some metallurgical and non-abrasive applications of SiC are emissive at high temperatures due to the SiC oxidation temperature (Biscay 2021). While emissions should be accounted for where they occur based on *2006 IPCC Guidelines*, emissions from SiC consumption are accounted for here until additional data on SiC consumption by end-use are available. The reporting category (2B5) includes emissions from the production of SiC, and the reporting category (2B10) includes emissions from the consumption of SiC.

To produce SiC, silica sand or quartz (SiO_2) is reacted with carbon (C) in the form of petroleum coke. A portion (about 35 percent) of the carbon contained in the petroleum coke is retained in the SiC. The remaining carbon is

emitted as CO_2, CH_4, or carbon monoxide (CO). The overall reaction is shown below, but in practice, it does not proceed according to stoichiometry:

$$SiO_2 + 3C \rightarrow SiC + 2CO \ (+ O_2 \rightarrow 2CO_2)$$

Carbon dioxide and CH_4 are also emitted during the production of calcium carbide, a chemical used to produce acetylene. Carbon dioxide is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter.

Markets for manufactured abrasives, including SiC, are heavily influenced by activity in the U.S. manufacturing sector, especially in the aerospace, automotive, furniture, housing, and steel manufacturing sectors. Specific applications of abrasive-grade SiC in 2018 included antislip abrasives, blasting abrasives, bonded abrasives, coated abrasives, polishing and buffing compounds, tumbling media, and wire-sawing abrasives (USGS 2021). Approximately 50 percent of SiC is used in metallurgical applications, which include primarily iron and steel production, and other non-abrasive applications, which include use in advanced or technical ceramics and refractories (USGS 2023a; Washington Mills 2023).

As a result of the economic downturn in 2008 and 2009, demand for SiC decreased in those years. Low-cost imports, particularly from China, combined with high relative operating costs for domestic producers, continue to put downward pressure on the production of SiC in the United States. Consumption of SiC in the United States has recovered somewhat from its low in 2009 to 2020; 2021 consumption data was withheld to avoid disclosing company proprietary data (USGS 1991b through 2021), and 2022 USGS data has not yet been released.

Silicon carbide was manufactured by two facilities in the United States, one of which produced primarily non-abrasive SiC (USGS 2021). USGS production values for the United States consists of SiC used for abrasives and for metallurgical and other non-abrasive applications (USGS 2021). During the COVID-19 pandemic in 2020, the U.S. Department of Homeland Security considered abrasives manufacturing part of the critical manufacturing sector, and as a result, pandemic "stay-at-home" orders issued in March 2020 did not affect the abrasives manufacturing industry. These plants remained at full operation (USGS 2021a). In 2022, imports and exports continued to recover from the negative effects of the COVID-19 pandemic (USGS 2023b). Consumption of SiC increased by approximately 27 percent from 2021 to 2022, rising above pre-pandemic levels (U.S. Census Bureau 2005 through 2022).

Carbon dioxide emissions from SiC production and consumption in 2022 were 0.2 MMT CO_2 Eq. (210 kt CO_2), which are about 14 percent lower than emissions in 1990 (see Table 4-43 and Table 4-44). Approximately 50 percent of these emissions resulted from SiC production, while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2022 were 0.01 MMT CO_2 Eq. (0.5 kt CH_4) (see Table 4-43 and Table 4-44). These tables indicate minor changes in emissions in recent years.

Table 4-43: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	+	+	+	+	+	+	+
SiC Consumption							
CO_2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-44: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	170	92	92	92	92	92	105
CH_4	1	+	+	+	+	+	+
SiC Consumption							
CO_2	73	121	93	84	62	80	105

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from the production of SiC are calculated using the Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Emissions of CO_2 from the consumption of SiC are a country-specific source calculated using a country-specific methodology based on available data. The *2006 IPCC Guidelines* do not provide guidance for estimating emissions from use of SiC or SiC consumption, but the country-specific methodology used is based on the stoichiometry of SiC consumption and is compatible with the *2006 IPCC Guidelines* and consistent with a Tier 1 approach.

Annual estimates of SiC production were multiplied by the default emission factors, as shown below:

Equation 4-78: *2006 IPCC Guidelines* Tier 1: Emissions from Carbide Production (Equation 3.11)

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1\ metric\ ton}{1000\ kg}\right)$$

where,

$E_{sc,CO2}$ = CO_2 emissions from production of SiC, metric tons

$EF_{sc,CO2}$ = Emission factor for production of SiC, metric ton CO_2/metric ton SiC

Q_{sc} = Quantity of SiC produced, metric tons

$E_{sc,CH4}$ = CH_4 emissions from production of SiC, metric tons

$EF_{sc,CH4}$ = Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines*:

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Production data includes silicon carbide manufactured for abrasive applications as well as for metallurgical and other non-abrasive applications (USGS 2021).

Silicon carbide industrial abrasives production data for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2021; USGS 2023a). Silicon carbide production data published by USGS have been rounded to the nearest 5,000 metric tons to avoid disclosing company proprietary data. For the period 1990 through 2001, reported USGS production data include production from two facilities located in Canada that ceased operations in 1995 and 2001. Using SiC production data from Canada (ECCC 2022), U.S. SiC production for 1990 through 2001 was adjusted to reflect only U.S. production.

Emissions from SiC consumption are calculated by multiplying the annual SiC consumption for metallurgical and other non-abrasive uses by the carbon content of SiC (about 30.0 percent), which is based on the molecular weight

of SiC, and converted to CO_2. This conversion calculation equates to 1.10 and is consistent with the IPCC default emission factor to calculate CO_2 emissions from the consumption of acetylene, a calcium carbide product, and demonstrates a methodology consistent with the *2006 IPCC Guidelines*. The amount of SiC used by other non-abrasive applications is determined by multiplying the annual SiC consumption by 50 percent (the percentage that the USGS allocates as usage by metallurgical and other non-abrasive applications) and then subtracting the amount of SiC used for metallurgical applications (USGS 1991a through 2021; USGS 2023a).

Emissions from SiC consumption are estimated for the entire time series using USGS consumption data (USGS 1991b through 2021) and data from the U.S. International Trade Commission (USITC) database on net imports and exports of SiC (U.S. Census Bureau 2005 through 2022) (Table 4-45). Total annual SiC consumption (utilization) was estimated by subtracting annual exports of SiC from the total of annual national SiC production and annual imports. Data on the annual consumption of SiC for metallurgical uses were obtained from USGS *Minerals Yearbook: Silicon* (USGS 1991b-2021; USGS 2023c). USGS withheld consumption data for metallurgical uses from publication for 2017, 2018, and 2021, and 2022 due to concerns of disclosing company-specific sensitive information, SiC consumption for 2017 and 2018 were estimated using 2016 values, and SiC consumption for 2021 and 2022 were estimated using the 2020 value (USGS 2023c). Additionally, as the USGS has not yet released the 2022 data, SiC consumption for 2022 was estimated using the 2020 value.

The petroleum coke portion of the total CO_2 process emissions from silicon carbide production is adjusted for within the Energy chapter, as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Table 4-45: Production and Consumption of Silicon Carbide (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production	65,000	35,000	35,000	35,000	35,000	35,000	40,000
SiC Consumption	132,465	220,149	168,526	152,412	113,756	146,312	191,133

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Silicon carbide production data published by the USGS is rounded to the nearest 5,000 tons and has been consistently reported at 35,000 tons since 2003 to avoid disclosure of company proprietary data. This translates to an uncertainty range of ±7 percent and a normal probability density function for SiC production (USGS 2021). There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative is to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced; however, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). EPA assigned an uncertainty of ±10 percent for the Tier 1 CO_2 and CH_4 emission factors for the SiC production processes, and using this suggested uncertainty provided in Section 3.6.3.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors. There is also uncertainty associated with the use or destruction of CH_4 generated from the process, in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses. EPA assigned an uncertainty range of ±5 percent for the primary data inputs for consumption (i.e., crude imports, ground and refined imports, crude exports, ground and refined exports, utilization [metallurgical applications]) to calculate overall uncertainty from SiC production, and using this suggested uncertainty provided in Section 3.6.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-46. Silicon carbide production and consumption CO_2 emissions from 2022 were estimated to be between 10 percent below and 10 percent above the emission estimate of 0.2 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 10 percent below and 11 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-46: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-10%	+10%
Silicon Carbide Production	CH_4	+	+	+	-10%	+11%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is initiating research for data on SiC consumption by end-use for consideration in updating emissions estimates from SiC consumption and to account for emissions where they occur. This planned improvement is subject to data availability and will be implemented in the medium- to long-term given significance of emissions.

EPA has not integrated aggregated facility-level GHGRP information to inform estimates of CO_2 and CH_4 from SiC production and consumption. The aggregated information (e.g., activity data and emissions) associated with silicon carbide did not meet criteria to shield underlying confidential business information (CBI) from public disclosure. EPA plans to examine the use of GHGRP silicon carbide emissions data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories. This planned improvement is ongoing and has not been incorporated into this *Inventory* report. This is a long-term planned improvement.

4.11 Titanium Dioxide Production (CRT Source Category 2B6)

Titanium dioxide (TiO_2) is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related carbon dioxide

(CO_2). The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2. The reporting category (2B6) includes emissions from production of TiO_2. In accordance with the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The chloride process is based on the following chemical reactions and does emit CO_2:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (rutile ore) to form CO_2. Since 2004, all TiO_2 produced in the United States has been produced using the chloride process, and a special grade of "calcined" petroleum coke is manufactured specifically for this purpose.

The principal use of TiO_2 is as a white pigment in paint, lacquers, and varnishes. It is also used as a pigment in the manufacture of plastics, paper, and other products. In 2022, U.S. TiO_2 production totaled 1,100,000 metric tons (USGS 2023b). Five plants produced TiO_2 in the United States in 2022.

Emissions of CO_2 from titanium dioxide production in 2022 were estimated to be 1.5 MMT CO_2 Eq. (1,474 kt CO_2), which represents an increase of 23 percent since 1990 (see Table 4-47 and Table 4-48). Compared to 2021, emissions from titanium dioxide production remained the same because production was consistent from 2021 to 2022. Annual production dipped in 2019 and 2020 and increased in 2021 and 2022.

Table 4-47: CO_2 Emissions from Titanium Dioxide (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1.2	1.8	1.5	1.3	1.3	1.5	1.5

Table 4-48: CO_2 Emissions from Titanium Dioxide (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1,195	1,755	1,541	1,340	1,340	1,474	1,474

Methodology and Time-Series Consistency

Emissions of CO_2 from TiO_2 production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual national TiO_2 production is multiplied by chloride process-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equation is as follows:

Equation 4-9: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Titanium Production (Equation 3.12)

$$E_{td} = EF_{td} \times Q_{td}$$

where,

E_{td} = CO_2 emissions from TiO_2 production, metric tons

EF_{td} = Emission factor (chloride process), metric ton CO_2/metric ton TiO_2

Q_{td} = Quantity of TiO_2 produced, metric tons

The petroleum coke portion of the total CO_2 process emissions from TiO_2 production is adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology

section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Data were obtained for the total amount of TiO_2 produced each year. For years prior to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate process plant in the United States closed; therefore, 100 percent of production since 2004 used the chloride process (USGS 2005). An emission factor of 1.34 metric tons CO_2/metric ton TiO_2 was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other carbon inputs.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines*. Titanium dioxide production data and the percentage of total TiO_2 production capacity that used the chloride process for 1990 through 2018 (see Table 4-49) were obtained through the U.S. Geological Survey (USGS) *Minerals Yearbook: Titanium* (USGS 1991 through 2022). Production data for 2019 and 2020 were obtained from the USGS Minerals Yearbook: Titanium, advanced data release of the 2020 tables (USGS 2023a). Production data for 2020 and 2021 were obtained from the *Minerals Commodity Summaries: Titanium and Titanium Dioxide* (USGS 2023b).[39] Data on the percentage of total TiO_2 production capacity that used the chloride process were not available for 1990 through 1993, so data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate process plant closed in September 2001, the chloride process percentage for 2001 was estimated (Gambogi 2002). By 2002, only one sulfate process plant remained online in the United States, and this plant closed in 2004 (USGS 2005).

Table 4-49: Titanium Dioxide Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production	979	1,310	1,150	1,000	1,000	1,100	1,100

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Each year, the USGS collects titanium industry data for titanium mineral and pigment production operations. If TiO_2 pigment plants do not respond, production from the operations is estimated based on prior year production levels and industry trends. Variability in response rates fluctuates from 67 to 100 percent of TiO_2 pigment plants over the time series. EPA currently uses an uncertainty range of ±5 percent and a normal probability density function for the primary data inputs (i.e., TiO_2 production and chloride process capacity values) to calculate overall uncertainty from TiO_2 production, and using this suggested uncertainty provided in Section 3.7.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Additionally, the EPA uses an uncertainty range of ±15 percent and a triangular probability density function for the CO_2 chloride process carbon consumption rate, and using this uncertainty provided in Section 3.7.2.2 of the *2006 IPCC Guidelines* is representative of operations in the United States. based on expert judgment (RTI 2023).

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated using petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing

[39] EPA has not integrated aggregated facility-level GHGRP information for titanium dioxide production facilities (40 CFR Part 98 Subpart EE). The relevant aggregated information (activity data, emission factor) from these facilities did not meet criteria to shield underlying CBI from public disclosure.

agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available. EPA assigned an uncertainty range of ±15 percent and a triangular probability density function for the Tier 1 CO_2 emission factor for the titanium dioxide (chloride route) production process, and using this uncertainty provided in Table 3.9 of the *2006 IPCC Guidelines* is representative of operations in the United States based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-49. Titanium dioxide consumption CO_2 emissions from 2022 were estimated to be between 1.3 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.5 MMT CO_2 Eq.

Table 4-50: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.5	1.3	1.7	-12%	+13%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Updated USGS data on TiO_2 production was available for 2019 and 2020, resulting in updated emissions estimates for those years. Compared to the previous *Inventory*, emissions for 2019 decreased by 9 percent (134 kt CO_2), and emissions for 2020 increased by 12 percent (147 kt CO_2).

Planned Improvements

EPA plans to examine the use of GHGRP titanium dioxide emissions and other data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[40] This planned improvement is ongoing and has not been

[40] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

incorporated into this *Inventory* report. This is a long-term planned improvement given the significance of these emissions.

4.12 Soda Ash Production (CRT Source Category 2B7)

Carbon dioxide (CO_2) is generated as a byproduct of calcining trona ore to produce soda ash (sodium carbonate, Na_2CO_3) and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. This reporting category (2B7) includes emissions from the production of soda ash by any of four processes, of which calcining trona ore is the only emissive process used in the United States. Emissions from soda ash consumption associated with glass production are reported under Section 4.3, glass production. Emissions from soda ash consumption not associated with glass production are reported under Section 4.4, other process uses of carbonates. Emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Calcining involves placing crushed trona ore into a kiln to convert sodium bicarbonate into crude sodium carbonate that will later be filtered into pure soda ash. The emission of CO_2 during trona-based production is based on the following reaction:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O(Trona) \rightarrow 3Na_2CO_3(Soda\ Ash) + 5H_2O + CO_2$$

Soda ash is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. The largest use of soda ash is for glass manufacturing. Emissions from soda ash used in glass production are reported under Section 4.3. In addition, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2018b). Internationally, two types of soda ash are produced: natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash production. Trona is the principal ore from which natural soda ash is made.

The United States represents about one-fifth of total world soda ash output (USGS 2023a). Only two states produce natural soda ash: Wyoming and California. Of these two states, net emissions of CO_2 from soda ash production were only calculated for Wyoming where trona ore is used.[41] Soda ash end uses in 2022 (excluding glass production) consisted of chemical production, 54 percent; other uses, 17 percent; wholesale distributors (e.g., for use in agriculture, water treatment, and grocery wholesale), 10 percent; soap and detergent manufacturing, 9 percent; flue gas desulfurization, 7 percent; water treatment, 2 percent; and pulp and paper production, 1 percent (USGS 2023b).[42]

[41] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A facility in a third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona ore in the state. For a brief time, sodium bicarbonate was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Prior to 2004, because the trona ore was mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

[42] Percentages may not add up to 100 percent due to independent rounding.

U.S. natural soda ash is competitive in world markets because it is generally considered a better-quality raw material than synthetically produced soda ash, and most of the world's soda ash is synthetic. Although the United States continues to be a major supplier of soda ash, China surpassed the United States in soda ash production in 2003, becoming the world's leading producer.

In 2022, CO_2 emissions from the production of soda ash from trona ore were 1.7 MMT CO_2 Eq. (1,704 kt CO_2) (see Table 4-51 and Table 4-52). Total emissions from soda ash production in 2022 decreased by approximately 1 percent compared to emissions in 2021, as soda ash production returned to 2018 levels observed before the COVID-19 pandemic. Emissions have increased by approximately 19 percent from 1990 levels.

Trends in emissions have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. The U.S. soda ash industry saw a decline in domestic and export sales caused by adverse global economic conditions in 2009, followed by a steady increase in production through 2019 before a significant decrease in 2020 due to the COVID-19 pandemic.

Table 4-51: CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7

Table 4-52: CO_2 Emissions from Soda Ash Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704

Methodology and Time-Series Consistency

Carbon dioxide emissions from soda ash production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. During the soda ash production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as byproducts of the calcination process. Carbon dioxide emissions from the calcination of trona ore can be estimated based on the chemical reaction shown above. Based on this formula and the IPCC default emission factor of 0.0974 metric tons CO_2 per metric ton of trona ore, both of which are consistent with an IPCC Tier 1 approach, one metric ton of CO_2 is emitted when approximately 10.27 metric tons of trona ore are processed (IPCC 2006).

Data is not currently available for the quantity of trona used in soda ash production. Because trona ore is used primarily for soda ash production, EPA assumes that all trona ore production was used in soda ash production. The activity data for trona ore production (see Table 4-53) for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2016 through 2017, 2018a, 2019, 2020, 2021, 2022b, 2023b). Soda ash production[43] data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. EPA will continue to analyze and assess opportunities to use facility-level data from EPA's GHGRP to improve the emission estimates for the soda ash production source category consistent with IPCC[44] and UNFCCC guidelines.

[43] EPA has assessed the feasibility of using emissions information (including activity data) from EPA's GHGRP program. At this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

[44] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

Table 4-53: Trona Ore Used in Soda Ash Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Trona Ore Use[a]	14,700	17,000	17,600	18,400	15,000	17,600	17,500

[a] Trona ore use is assumed to be equal to trona ore production.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Emission estimates from soda ash production have relatively low associated uncertainty levels because reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The emission factor used for this estimate assumes the ore is 100 percent pure and likely overestimates the emissions from soda ash manufacture. The average water-soluble sodium carbonate-bicarbonate content for ore mined in Wyoming ranges from 85.5 to 93.8 percent (USGS 1995c).

EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process, based on EPA's GHGRP. Soda ash production data was collected by the USGS from voluntary surveys. A survey request was sent to each of the five soda ash producers, all of which responded, representing 100 percent of the total production data (USGS 2023b). EPA assigned an uncertainty range of ±5 percent for trona production, and using the suggested uncertainty provided in Section 3.8.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of -15 percent to 0 percent range for the trona emission factor, based on expert judgment on the purity of mined trona (USGS 1995c). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probability density function was assigned for the emission factor.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-54. Soda ash production CO_2 emissions for 2022 were estimated to be between 1.5 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below and 8 percent above the emission estimate of 1.7 MMT CO_2 Eq.

Table 4-54: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production	CO_2	1.7	1.5	1.7	-9%	+8%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 emissions from soda ash production.

4.13 Petrochemical Production (CRT Source Category 2B8)

The production of some petrochemicals results in carbon dioxide (CO_2) and methane (CH_4) emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. This reporting category (2B8) includes CO_2 emissions from the production of acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol, and CH_4 emissions from the production of acrylonitrile. The petrochemical industry uses primary fossil fuels (i.e., natural gas, coal, petroleum, etc.) for non-fuel purposes in the production of carbon black and other petrochemicals. Per the IPCC methodological guidance, emissions from fuels and feedstocks transferred out of the system for use in energy purposes (e.g., indirect or direct process heat or steam production) are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Worldwide, more than 90 percent of acrylonitrile (vinyl cyanide, C_3H_3N) is made by way of direct ammoxidation of propylene with ammonia (NH_3) and oxygen over a catalyst. This process is referred to as the SOHIO process, named after the Standard Oil Company of Ohio (SOHIO) (IPCC 2006). The primary use of acrylonitrile is as the raw material for the manufacture of acrylic and modacrylic fibers. Other major uses include the production of plastics (acrylonitrile-butadiene-styrene [ABS] and styrene-acrylonitrile [SAN]), nitrile rubbers, nitrile barrier resins, adiponitrile, and acrylamide. All U.S. acrylonitrile facilities use the SOHIO process (AN 2014). The SOHIO process involves a fluidized bed reaction of chemical-grade propylene, ammonia, and oxygen over a catalyst. The process produces acrylonitrile as its primary product, and the process yield depends on the type of catalyst used and the process configuration. The ammoxidation process produces byproduct CO_2, carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock and produces other hydrocarbons from side reactions.

Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States to produce carbon black is the furnace black (or oil furnace) process. In the furnace black process, carbon black oil (a heavy aromatic liquid) is continuously injected into the combustion zone of a natural gas-fired furnace. Furnace heat is provided by the natural gas and a portion of the carbon black feedstock; the remaining portion of the carbon black feedstock is pyrolyzed to carbon black. The resultant CO_2 and uncombusted CH_4 are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Three facilities in the United States use other types of carbon black processes. Specifically, one facility produces carbon black by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), a second facility produces carbon black by the thermal cracking of other hydrocarbons (i.e., thermal black process), and a third facility produces carbon black by the open burning of carbon black feedstock (i.e., lamp black process) (EPA 2000).

Ethylene (C_2H_4) is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE); polyvinyl chloride (PVC); ethylene dichloride; ethylene oxide; and ethylbenzene. Virtually all ethylene is produced from steam cracking of ethane, propane, butane, naphtha, gas oil, and other feedstocks. The representative chemical equation for steam cracking of ethane to ethylene is shown below:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

Small amounts of CH_4 are also generated from the steam cracking process. In addition, CO_2 and CH_4 emissions result from combustion units.

Ethylene dichloride ($C_2H_4Cl_2$) is used to produce vinyl chloride monomer, which is the precursor to polyvinyl chloride (PVC). Ethylene dichloride was also used as a fuel additive until 1996 when leaded gasoline was phased out. Ethylene dichloride is produced from ethylene by either direct chlorination, oxychlorination, or a combination of the two processes (i.e., the "balanced process"); most U.S. facilities use the balanced process. The direct chlorination and oxychlorination reactions are shown below:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (direct chlorination)}$$

$$C_2H_4 + \tfrac{1}{2}O_2 + 2HCl \rightarrow C_2H_4Cl_2 + 2H_2O \text{ (oxychlorination)}$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \text{ (direct oxidation of ethylene during oxychlorination)}$$

In addition to the byproduct CO_2 produced from the direct oxidation of the ethylene feedstock, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene oxide (C_2H_4O) is used in the manufacture of glycols, glycol ethers, alcohols, and amines. Approximately 70 percent of ethylene oxide produced worldwide is used in the manufacture of glycols, including monoethylene glycol. Ethylene oxide is produced by reacting ethylene with oxygen over a catalyst. The oxygen may be supplied to the process through either an air (air process) or a pure oxygen stream (oxygen process). The byproduct CO_2 from the direct oxidation of the ethylene feedstock is removed from the process vent stream using a recycled carbonate solution, and the recovered CO_2 may be vented to the atmosphere or recovered for further utilization in other sectors, such as food production (IPCC 2006). The combined ethylene oxide reaction and byproduct CO_2 reaction is exothermic and generates heat, which is recovered to produce steam for the process. The ethylene oxide process also produces other liquid and off-gas byproducts (e.g., ethane that may be burned for energy recovery within the process. Almost all facilities, except one in Texas, use the oxygen process to manufacture ethylene oxide (EPA 2008).

Methanol (CH_3OH) is a chemical feedstock most often converted into formaldehyde, acetic acid and olefins. It is also an alternative transportation fuel, as well as an additive used by municipal wastewater treatment facilities in the denitrification of wastewater. Methanol is most commonly synthesized from a synthesis gas (i.e., "syngas" – a mixture containing H_2, CO, and CO_2) using a heterogeneous catalyst. There are a number of process techniques that can be used to produce syngas. Worldwide, steam reforming of natural gas is the most common method; most methanol producers in the United States also use steam reforming of natural gas to produce syngas. Other syngas production processes in the United States include partial oxidation of natural gas and coal gasification.

Emissions of CO_2 and CH_4 from petrochemical production in 2022 were 28.8 MMT CO_2 Eq. (28,788 kt CO_2) and 0.005 MMT CO_2 Eq. (0.17 kt CH_4), respectively (see Table 4-55 and Table 4-56). Carbon dioxide emissions from petrochemical production are driven primarily from ethylene production, while CH_4 emissions are only from acrylonitrile production. Since 1990, total CO_2 emissions from petrochemical production increased by 43 percent, and CH_4 emissions declined by 22 percent. Emissions of CO_2 were 6 percent lower in 2022 than in 2021, and emissions of CH_4 were 12 percent higher in 2022 than in 2021. The increase in CO_2 emissions since 1990 is due primarily to increased ethylene and methanol production, which have been driven by the increased natural gas production in the United States. The reduction in CO_2 emissions since 2021 is due to a reduction in emissions from ethylene production, despite an increase in ethylene production. Since CH_4 emissions from acrylonitrile are calculated using a Tier 1 approach based on production as the activity data, the decrease in CH_4 emissions since 1990 and the increase since 2021 correspond with changes in the production levels for acrylonitrile.

Table 4-55: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**
Carbon Black	3.4	4.3	3.4	3.3	2.6	3.0	3.1
Ethylene	13.1	19.0	19.4	20.7	20.7	22.8	20.7

Ethylene Dichloride	0.3	0.5	0.4	0.5	0.5	0.4	0.4
Ethylene Oxide	1.1	1.5	1.3	1.4	1.7	1.9	1.7
Methanol	1.0	0.3	1.4	1.6	1.6	1.7	2.0
Acrylonitrile	1.2	1.3	1.3	1.0	0.9	0.9	1.0
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+
Total	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-56: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20,075**	**26,882**	**27,200**	**28,483**	**27,926**	**30,656**	**28,788**
Carbon Black	3,381	4,269	3,440	3,300	2,610	3,000	3,060
Ethylene	13,126	19,024	19,400	20,700	20,700	22,800	20,700
Ethylene Dichloride	254	455	440	503	456	376	428
Ethylene Oxide	1,123	1,489	1,300	1,370	1,680	1,930	1,650
Methanol	977	319	1,370	1,620	1,630	1,700	2,000
Acrylonitrile	1,214	1,325	1,250	990	850	850	950
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt CH_4.

Note: Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 were calculated using the estimation methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO_2 and CH_4 emissions from production of acrylonitrile,[45] and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO_2 emissions from production of carbon black, ethylene oxide, ethylene, ethylene dichloride, and methanol, as CO_2 emissions from petrochemical production is a key category. The Tier 2 method for petrochemicals is a total feedstock carbon mass balance method used to estimate total CO_2 emissions, but it is not applicable for estimating CH_4 emissions.

As noted in the *2006 IPCC Guidelines*, the Tier 2 total feedstock carbon mass balance method is based on the assumption that all of the carbon input to the process is converted either into primary and secondary products or into CO_2. Further, the guideline states that while the total carbon mass balance method estimates total carbon emissions from the process, it does not directly provide an estimate of the amount of the total carbon emissions emitted as CO_2, CH_4, or non-CH_4 volatile organic compounds (NMVOCs). This method accounts for all the carbon as CO_2, including CH_4.

A methodology refinement for emissions from methanol production was implemented in this *Inventory* to transition from a Tier 1 method to a country-specific approach similar to a Tier 2 method, using the process CO_2 emissions reported to Subpart X of the GHGRP. As part of this refinement, CH_4 emissions from methanol production for every year in the time series are now included in the CO_2 emissions estimates to avoid double counting because the GHGRP reporting method is a mass balance method under which all carbon input to the process is assumed to be converted either into primary and secondary products or into CO_2.

[45] EPA has not integrated aggregated facility-level GHGRP information for acrylonitrile production. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Note, a subset of facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor CO_2 emissions from process vents and/or stacks from stationary combustion units or use the optional combustion methodology for ethylene production facilities. These facilities are required to also report CO_2, CH_4 and N_2O emissions from combustion of process off-gas in flares. The CO_2 emissions from flares are included in aggregated CO_2 results. Analysis of aggregated annual reports from those facilities shows that flared CH_4 and N_2O emissions are less than 300 kt CO_2 Eq./year. Since data is only available from a subset of facilities and not consistently reported over time and since CH_4 and N_2O emissions are shown to be insignificant, they are excluded from this analysis. See the planned improvements section below and Annex 5.

Carbon Black, Ethylene, Ethylene Dichloride, and Ethylene Oxide

2010 through 2022

Carbon dioxide emissions and national production for carbon black, ethylene, ethylene dichloride, and ethylene oxide were aggregated directly from EPA's GHGRP dataset for 2010 through 2022 (EPA 2023).

These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of carbon black, ethylene, ethylene dichloride, ethylene oxide. In 2022, data reported to the GHGRP included 3,060,000 metric tons of CO_2 emissions from carbon black production; 20,700,000 metric tons of CO_2 from ethylene production; 428,000 metric tons of CO_2 from ethylene dichloride production; and 1,650,000 metric tons of CO_2 from ethylene oxide production.

Since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Most petrochemical production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each petrochemical process unit to estimate facility-level process CO_2 emissions; ethylene production facilities also have a third option. The mass balance method is used by most facilities[46] and assumes that all the carbon input is converted into primary and secondary products or is emitted to the atmosphere as CO_2. To apply the mass balance, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. To apply the optional combustion methodology, ethylene production facilities must measure the quantity, carbon content, and molecular weight of the fuel to a stationary combustion unit when that fuel includes any ethylene process off-gas. These data are used to calculate the total CO_2 emissions from the combustion unit. The facility must also estimate the fraction of the emissions that is attributable to burning the ethylene process off-gas portion of the fuel. This fraction is multiplied by the total emissions to estimate the emissions from ethylene production. The QA/QC and Verification section below has a discussion of non-CO_2 emissions from ethylene production facilities.

All non-energy uses of residual fuel and some non-energy uses of "other oil" are assumed to be used in the production of carbon black; therefore, consumption of these fuels is adjusted for within the Energy chapter to avoid double-counting of emissions from fuel used in the carbon black production presented here within IPPU sector. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Section 3.1 and Annex 2.1.

1990 through 2009

Prior to 2010, for carbon black, ethylene, ethylene dichloride, and ethylene oxide processes, an average national CO_2 emission factor was calculated based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO_2 emissions. For these 4 types of petrochemical processes, CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for petrochemical type "i"

[46] A few facilities producing ethylene dichloride, ethylene, and methanol used CO_2 CEMS; those CO_2 emissions have been included in the aggregated GHGRP emissions presented here.

with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2013 (EPA 2023). The years 2010 through 2013 were used in the development of carbon dioxide emission factors as these years are more representative of operations in 1990 through 2009 for these facilities. The average emission factors for each petrochemical type were applied across all prior years because petrochemical production processes in the United States have not changed significantly since 1990, though some operational efficiencies have been implemented at facilities over the time series.

The average country-specific CO_2 emission factors that were calculated from the GHGRP data are as follows:

- 2.59 metric tons CO_2/metric ton carbon black produced
- 0.79 metric tons CO_2/metric ton ethylene produced
- 0.040 metric tons CO_2/metric ton ethylene dichloride produced
- 0.46 metric tons CO_2/metric ton ethylene oxide produced

Annual production data for carbon black for 1990 through 2009 were obtained from the International Carbon Black Association (Johnson 2003 and 2005 through 2010). Annual production data for ethylene, ethylene dichloride, and ethylene oxide for 1990 through 2009 were obtained from the American Chemistry Council's (ACC) *Business of Chemistry* (ACC 2023).

Methanol

2015 through 2022

Carbon dioxide emissions and national production for methanol were aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023). These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of methanol. In 2022, data reported to the GHGRP included 2,000,000 metric tons of CO_2 emissions from methanol production.

As noted above, since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Methanol production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each methanol process unit to estimate facility-level process CO_2 emissions. Most methanol production facilities use the mass balance method. As noted above, when using the mass balance method, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. For 2010 to 2014, the methanol data reported to GHGRP is considered CBI; therefore, the direct use of the GHGRP data starts with the 2015 reported information.

1990 through 2014

In this *Inventory*, similar to the methodology for other petrochemicals that utilize GHGRP data, an average national CO_2 emission factor for years prior to 2015 was calculated for methanol production based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2014) to estimate CO_2 emissions. Methanol CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for methanol with annual production for methanol and then averaging the derived emission factors obtained for each year 2015 through 2022. The average country-specific CO_2 emission factor from the GHGRP data for these years was determined to be 0.26 metric tons CO_2/metric ton methanol produced. Annual methanol production data for 1990 through 2014 were obtained from the ACC's *Business of Chemistry* (ACC 2023). The average country-specific CO_2 emission factor from the GHGRP data is lower than the IPCC Tier 1 emission factor of 0.67 metric tons CO_2/metric ton methanol produced value that was used in previous versions of the *Inventory*. The main difference between the IPCC Tier 1 emission factor and the GHGRP emission factor is that the IPCC emission factor includes emissions from combustion of natural gas fuel in the reformer as well as vented CO_2 from the process; therefore, the use of the IPCC Tier 1 emission factor would double count emissions from natural gas combustion in the IPPU

chapter and the Energy chapter. EPA already accounts for emissions from combustion of natural gas fuel in the reformer as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Acrylonitrile

Carbon dioxide and methane emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Acrylonitrile emissions represent about 3 percent of total petrochemical emissions in 2022 so a Tier 1 approach is deemed acceptable, and higher Tier methods could not be used due to data sensitivities which are described below. Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2022. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH_4/metric ton acrylonitrile produced
- 1.00 metric tons CO_2/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2022 were obtained from ACC's *Business of Chemistry* (ACC 2023). EPA is unable to apply the aggregated facility-level GHGRP information for acrylonitrile production needed for a Tier 2 approach due to sensitive nature of reported data. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Production of each type of petrochemical are shown in Table 4-57.

Table 4-57: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2018	2019	2020	2021	2022
Carbon Black	1,307	1,651	1,280	1,210	990	1,140	1,170
Ethylene	16,542	23,975	30,500	32,400	33,500	34,700	35,400
Ethylene Dichloride	6,283	11,260	12,500	12,600	11,900	11,500	12,100
Ethylene Oxide	2,429	3,220	3,310	3,800	4,680	4,860	5,310
Methanol	3,750	1,225	5,830	6,460	6,580	7,110	8,030
Acrylonitrile	1,214	1,325	1,250	990	850	850	950

As noted earlier in the introduction section of the Petrochemical Production section, the allocation and reporting of emissions from both fuels and feedstocks transferred out of the system for use in energy purposes to the Energy chapter differs slightly from the *2006 IPCC Guidelines*. According to the *2006 IPCC Guidelines*, emissions from fuel combustion from petrochemical production should be allocated to this source category within the IPPU chapter. Due to national circumstances, EIA data on primary fuel for feedstock use within the energy balance are presented by commodity only, with no resolution on data by industry sector (i.e., petrochemical production). In addition, under EPA's GHGRP, reporting facilities began reporting in 2014 on annual feedstock quantities for mass balance and CEMS methodologies (79 FR 63794), as well as the annual average carbon content of each feedstock (and molecular weight for gaseous feedstocks) for the mass balance methodology beginning in reporting year 2017 (81 FR 89260).[47] The United States is currently unable to report non-energy fuel use from petrochemical production under the IPPU chapter due to CBI issues. Therefore, consistent with *2006 IPCC Guidelines*, fuel consumption data reported by EIA are adjusted to account for these overlaps to avoid double-counting. More information on the non-energy use of fossil fuel feedstocks for petrochemical production can be found in Annex 2.3.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ethylene production, ethylene dichloride production, and ethylene oxide production spliced activity data from two different sources: ACC for 1990 through 2009 and GHGRP for 2010 through 2022. The methodology for methanol production spliced activity data from two different sources: ACC for 1990 through 2014 and GHGRP for 2015 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap

[47] See https://www.epa.gov/ghgreporting/historical-rulemakings.

technique was applied to compare the two data sets for years where there was overlap. For ethylene production, the data sets were determined to be consistent, and adjustments were not needed. For ethylene dichloride production, ethylene oxide production, and methanol production, the data sets were determined to be inconsistent. The GHGRP data includes production of ethylene dichloride and ethylene oxide as intermediates, while it is unclear if the ACC data does. Methanol production data from GHGRP are significantly higher than the ACC data for every year since 2015; the reason for the difference is not clear. Therefore, no adjustments were made to the ethylene dichloride, ethylene oxide, and methanol activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent. The methodology for carbon black production also spliced activity data from two different sources: ICBA for 1990 through 2009 and GHGRP for 2010 through 2022. The overlap technique was applied to these data for 2010 and 2011. The data sets were determined to be consistent, and adjustments were not needed.

Uncertainty

The CO_2 and CH_4 emission factors used for acrylonitrile production are based on a limited number of studies. Using plant-specific factors instead of default or average factors could increase the accuracy of the emission estimates; however, such data were not available for the current *Inventory* report. For acrylonitrile, EPA assigned an uncertainty range of ±60 percent for the CO_2 emission factor, ±10 percent for the CH_4 emission factor, and a normal probability density function for both, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment, (RTI 2023). The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, ethylene oxide, and methanol are based on reported GHGRP data. Refer to the Methodology section for more details on how these emissions were calculated and reported to EPA's GHGRP. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-58. Petrochemical production CO_2 emissions from 2022 were estimated to be between 27.6 and 30.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below to 4 percent above the emission estimate of 28.8 MMT CO_2 Eq. Petrochemical production CH_4 emissions from 2022 were estimated to be between 0.0 and 0.01 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below to 14 percent above the emission estimate of 0.005 MMT CO_2 Eq.

Table 4-58: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Petrochemical Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	28.8	27.6	30.0	-4%	+4%
Petrochemical Production	CH_4	+	0.0	0.01	-14%	+14%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For petrochemical production, QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan, as described in the QA/QC and Verification Procedures section of the IPPU chapter and Annex 8. Source-specific quality control measures for this category included the QA/QC requirements and verification procedures of EPA's GHGRP. More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).[48] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[49] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported production data by petrochemical type against external datasets.

For ethylene, ethylene dichloride and ethylene oxide, it is possible to compare CO_2 emissions calculated using the GHGRP data to the CO_2 emissions that would have been calculated using the Tier 1 approach if GHGRP data were not available. For ethylene, the GHGRP emissions were within ±8 percent of the emissions calculated using the Tier 1 approach prior to 2018; for 2018 through 2022, the GHGRP emissions were between 76 percent and 87 percent of what would be calculated using the Tier 1 approach. For ethylene dichloride, the GHGRP emissions are typically higher than the Tier 1 emissions by up to 25 percent, but in 2010 and 2021, GHGRP emissions were slightly lower than the Tier 1 emissions. For ethylene oxide, GHGRP emissions typically vary from the Tier 1 emissions by up to ±20 percent, but in 2021 and 2022, the GHGRP emissions were significantly higher than the Tier 1 emissions. This was likely due to GHGRP data capturing the production of ethylene oxide as an intermediate in the onsite production of ethylene glycol.

For methanol, GHGRP production data was consistently higher than ACC production data in all years between 2015 and 2022. Even though the GHGRP production was higher than the ACC production, the GHGRP CO_2 emissions estimated using the methodology refinement in this *Inventory* are significantly lower than the emissions calculated using the Tier 1 approach in all years between 2015 and 2022. Additionally, there is a trend towards increasing differences over these years starting with an 873 kt CO_2 difference in 2015 and increasing to a 3,000 kt CO_2 difference in 2022. GHGRP emissions were between 43 percent and 61 percent of the Tier 1 emissions in 2015 and 2018, respectively. As discussed in the Methodology and Time-Series Consistency section above, EPA has determined that using the IPCC Tier 1 emissions factor to calculate methanol emissions results in double counting of natural gas combustion emissions in both this chapter and in the Energy chapter; therefore, use of the GHGRP derived emissions is deemed appropriate. For the years 1990 through 2014, the use of the GHGRP derived emission factor also results in lower emissions than those calculated using the IPCC Tier 1 emission factor. While this avoids the double counting of emissions with the Energy chapter, as described below in the Planned Improvements section, EPA intends to examine the emissions from methanol facilities that report to the GHGRP and may have been operating prior to 2010 to assess whether a more specific process-only emission factor can be developed from the GHGRP data for use in estimating CO_2 emissions from methanol production in 1990 through 2014.

EPA's GHGRP mandates that all petrochemical production facilities report their annual emissions of CO_2, CH_4, and N_2O from each of their petrochemical production processes. Source-specific quality control measures for the Petrochemical Production category included the QA/QC requirements and verification procedures of EPA's GHGRP. The QA/QC requirements differ depending on the calculation methodology used.

[48] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[49] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

As part of a planned improvement effort, EPA has assessed the potential of using GHGRP data to estimate CH_4 emissions from ethylene production. As discussed in the Methodology section above, CO_2 emissions from ethylene production in this chapter are based on data reported under the GHGRP, and these emissions are calculated using a Tier 2 approach that assumes all of the carbon in the fuel (i.e., ethylene process off-gas) is converted to CO_2. Ethylene production facilities also calculate and report CH_4 emissions under the GHGRP when they use the optional combustion methodology. The facilities calculate CH_4 emissions from each combustion unit that burns off-gas from an ethylene production process unit using a Tier 1 approach based on the total quantity of fuel burned, a default or measured higher heating value, and a default emission factor. Because multiple other types of fuel in addition to the ethylene process unit off-gas may be burned in these combustion units, the facilities also report an estimate of the fraction of emissions that is due to burning the ethylene process off-gas component of the total fuel. Multiplying the total emissions by the estimated fraction provides an estimate of the CH_4 emissions from the ethylene production process unit. These ethylene production facilities also calculate CH_4 emissions from flares that burn process vent emissions from ethylene processes. The CO_2 emissions are calculated using either a Tier 2 approach based on measured gas volumes and measured carbon content or higher heating value, or a Tier 1 approach based on the measured gas flow and a default emission factor; the CH_4 emissions are calculated based on a Tier 1 approach using the CO_2 emissions and default emission factors. Nearly all ethylene production facilities use the optional combustion methodology under the GHGRP. The CH_4 emissions from ethylene production under the GHGRP have not been included in this chapter because this approach double counts carbon (i.e., all of the carbon in the CH_4 emissions is also included in the CO_2 emissions from the ethylene process units). EPA continues to assess the GHGRP data for ways to better disaggregate the data and incorporate it into the *Inventory*.

These facilities are also required to report emissions of N_2O from combustion of ethylene process off-gas in both stationary combustion units and flares. Facilities using CEMS (consistent with a Tier 3 approach) are also required to report emissions of CH_4 and N_2O from combustion of petrochemical process-off gases in flares. Preliminary analysis of the aggregated reported CH_4 and N_2O emissions from facilities using CEMS and N_2O emissions from facilities using the optional combustion methodology suggests that these annual emissions are less than 0.4 percent of total petrochemical emissions, which is not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these N_2O emissions in future reports to enhance completeness. Future QC efforts to validate the use of Tier 1 default emission factors and report on the comparison of Tier 1 emission estimates and GHGRP data are described below in the Planned Improvements section.

Recalculations Discussion

A methodology refinement for calculating emissions from methanol production was implemented in this *Inventory*. As discussed in the Methodology and Time-Series Consistency section, the previously used Tier 1 approach was replaced with a country-specific approach similar to a Tier 2 method based on emissions aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023) and an average country-specific CO_2 emission factor from the GHGRP data applied to production data from ACC's *Business of Chemistry* for 1990 through 2014 (ACC 2023). For 2015 through 2021, these changes resulted in a reduction in the reported CO_2 emissions between 43 percent (873 kt) in 2015 to 61 percent (2,110 kt) in 2018. For 1990 through 2014, the refinement resulted in a reduction of 61 percent each year (287 kt in 2011 to 2,449 kt in 1997).

Additionally, CH_4 emissions previously reported from methanol production were reduced to zero for all years of the time series because, as noted above in the Methodology and Time Series Consistency section, the methodology refinement is based on the assumption that all carbon input to the process is converted either to primary and secondary products or to CO_2.

Planned Improvements

Improvements include completing category-specific QC of activity data and emission factors, along with further assessment of CH_4 and N_2O emissions to enhance completeness in reporting of emissions from U.S. petrochemical

production, pending resources, significance and time-series consistency considerations. For example, EPA is planning additional assessment of fuel combustion emissions data reported by methanol production facilities for ways to estimate process-based emissions in the *Inventory* separately from combustion emissions for 1990 through 2014. If the GHGRP data can be categorized by type of methanol process design, it may be possible to use GHGRP data for single reformer process units to develop a ratio of process-to-total emissions to adjust the IPCC emission factor. Potential difficulties with this analysis are that some of the methanol producing facilities also produce other chemicals and the combustion unit names may not clearly identify the process unit to which they apply, and some combustion unit data may be aggregated for multiple combustion units. The EPA is also planning additional assessment of ways to use CH_4 data from the GHGRP in the *Inventory*. One possible approach EPA is assessing would be to adjust the CO_2 emissions from the GHGRP downward by subtracting the carbon that is also included in the reported CH_4 emissions, per the discussion in the Petrochemical Production QA/QC and Verification section, above. As of this current report, timing and resources have not allowed EPA to complete these analyses of activity data, emissions, and emission factors but they remain priority improvements within the IPPU chapter.

Pending resources, a secondary potential improvement for this source category would focus on continuing to analyze the fuel and feedstock data from EPA's GHGRP to better disaggregate energy-related emissions and allocate them more accurately between the Energy and IPPU sectors of the *Inventory*. EPA will continue to look for ways to incorporate this data into future Inventories that will allow for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter. This planned improvement is still under development and has not been completed to report on progress in this current *Inventory*.

4.14 HCFC-22 Production (CRT Source Category 2B9a)

This reporting category (2B9a) includes by-product emissions of HCFC-23 (trifluoromethane or CHF_3) from production of HCFC-22 (chlorodifluoromethane). HFC-23 is generated as a byproduct during the manufacture of HCFC-22, which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Between 2000 and 2007, U.S. production fluctuated but generally remained above 1990 levels. In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses was phased out in 2020 under the U.S. Clean Air Act.[50] Feedstock production, however, is permitted to continue indefinitely. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where x + y = 5), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful

[50] As construed, interpreted, and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer* [42 U.S.C. §7671m(b), CAA §614].

byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Two facilities produced HCFC-22 in the United States in 2022. Emissions of HFC-23 from this activity in 2022 were estimated to be 1.8 MMT CO_2 Eq. (0.1 kt) (see Table 4-59 and Table 4-60). This quantity represents an 18 percent increase from 2021 emissions and a 95 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The decrease from 2021 emissions was caused by both a decrease in the HFC-23 emission rate at one plant and a decrease in the total quantity of HCFC-22 produced. The long-term decrease in the emission rate is primarily attributable to six factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990; (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22; (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated; (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale; (e) another plant began destroying HFC-23; and (f) the same plant, whose emission rate was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

Emissions from HCFC-22 production are reported under fluorochemical production (CRT category 2B9) in this *Inventory*, which also includes the production of fluorochemicals other than HCFC-22 described further in section 4.15 of this chapter.

Table 4-59: HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	38.6	16.8	2.7	3.1	1.8	2.2	1.8

Table 4-60: HFC-23 Emissions from HCFC-22 Production (kt HFC-23)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	3	1	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

To estimate HFC-23 emissions for five of the eight HCFC-22 plants that have operated in the United States since 1990, methods comparable to the Tier 3 methods in the *2006 IPCC Guidelines* (IPCC 2006) were used throughout the time series. Emissions for 2010 through 2022 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's Greenhouse Gas Reporting Program (GHGRP). EPA's GHGRP mandates that all HCFC-22 production facilities report their annual emissions of HFC-23 from HCFC-22 production processes and HFC-23 destruction processes. Previously, data were obtained by EPA through collaboration with an industry association that received voluntarily reported HCFC-22 production and HFC-23 emissions annually from all U.S. HCFC-22 producers from 1990 through 2009. These emissions were aggregated and reported to EPA on an annual basis.

For the other three plants, the last of which closed in 1993, methods comparable to the Tier 1 method in the *2006 IPCC Guidelines* were used. Emissions from these three plants have been calculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure (or, for the plants that have since closed, measured) concentrations of HFC-23 as well as mass flow rates of process streams to estimate their generation of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. One plant that releases a small fraction of its byproduct HFC-23 periodically measures HFC-23 concentrations at process vents using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

To estimate 1990 through 2009 emissions, reports from an industry association were used that aggregated HCFC-22 production and HFC-23 emissions from all U.S. HCFC-22 producers and reported them to EPA (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010). To estimate 2010 through 2022 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through EPA's GHGRP were analyzed. In 1997 and 2008, comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production were performed (RTI 1997; RTI 2008). The 1997 and 2008 reviews enabled U.S. totals to be reviewed, updated, and where necessary, corrected. The reviews also allowed plant-level uncertainty analyses (Monte-Carlo simulations) to be performed for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-61.

Table 4-61: HCFC-22 Production (kt)

Year	1990	2005	2012	2018	2019	2020	2021	2022
Production	139	156	96	C	C	C	C	C

C (CBI)

Note: HCFC-22 production in 2013 through 2022 is considered confidential business information (CBI) as there were only two producers of HCFC-22 in those years.

Uncertainty

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo stochastic simulation for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo stochastic simulation for 2006 were applied to the U.S. emission estimate for 2022. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the two remaining plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants has changed between 2006 and 2022 (because one plant has closed), the plant that currently accounts for most emissions had a relative uncertainty in its 2006 (as well as 2005) emissions estimate that was similar to the relative uncertainty for total U.S. emissions. Thus, the closure of one plant is not likely to have a large impact on the uncertainty of the national emission estimate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-62. HFC-23 emissions from HCFC-22 production were estimated to be between 1.7 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 1.8 MMT CO_2 Eq.

Table 4-62: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	1.8	1.7	2.0	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[51] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the HCFC-22 Production category. Under EPA's GHGRP, HCFC-22 producers are required to (1) measure concentrations of HFC-23 and HCFC-22 in the product stream at least weekly using equipment and methods (e.g., gas chromatography) with an accuracy and precision of 5 percent or better at the concentrations of the process samples, (2) measure mass flows of HFC-23 and HCFC-22 at least weekly using measurement devices (e.g., flowmeters) with an accuracy and precision of 1 percent of full scale or better, (3) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable standards and suitable methods published by a consensus standards organization, (4) calibrate gas chromatographs at least monthly through analysis of certified standards, and (5) document these calibrations.

Recalculations Discussion

The 2019 emissions estimate increased by 0.05 kg of HFC-23 to reflect newly reported emissions from a facility that destroys HFC-23. This increased the 2019 emissions estimate by two ten thousandths of a percent.

Planned Improvements

At this time, there are no specific planned improvements for estimating HFC-23 emissions from HCFC-22 production.

4.15 Production of Fluorochemicals Other Than HCFC-22 (CRT Source Category 2B9b)

This reporting category, fluorochemical production (2B9b), facilities in the United States produced or transformed approximately 200 fluorinated gases other than HCFC-22 in 2022, including saturated and unsaturated hydrofluorocarbons (HFCs), saturated and unsaturated perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluoroethers (HFEs), perfluoroalkylamines, and dozens of others. Emissions from fluorochemical production may include emissions of the intentionally manufactured chemical as well as reactant and by-product emissions. The compounds emitted depend upon the production or transformation process, but may include, e.g., HFCs, PFCs, SF_6, nitrous oxide (N_2O), NF_3, and many others. Potential sources of fluorinated GHG emissions at fluorochemical production facilities include process vents, equipment leaks, and evacuating returned

[51] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

containers[52] Production-related emissions of fluorinated GHGs occur from both process vents and equipment leaks. Process vent emissions occur from manufacturing equipment such as reactors, distillation columns, and packaging equipment. Equipment leak emissions, or fugitive emissions, occur from valves, flanges, pump seals, compressor seals, pressure relief valves, connectors, open-ended lines, and sampling connections. In addition, users of fluorinated GHGs may return empty containers (e.g., cylinders) to the production facility for reuse; prior to reuse, the residual fluorinated GHGs (often termed "heels") may be evacuated from the container and are a potential emission source. In many cases, these "heels" are recovered or exhausted to a treatment device for destruction. In other cases, however, they are released into the atmosphere.[53]

Emissions of all HFCs, PFCs, NF_3, and SF_6 from production of fluorochemicals other than hydrochlorofluorocarbon (HCFC)-22 are presented in Table 4-63 below for the years 1990, 2005, and the period 2018 to 2022. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The fluorinated GHG emissions reported under the Greenhouse Gas Reporting Program (GHGRP) include emissions of HFCs, PFCs, SF_6, NF_3, and numerous "other" fluorinated GHGs, such as octafluorotetrahydrofuran (C_4F_8O), trifluoromethyl sulfur pentafluoride (SF_5CF_3), and hexafluoropropylene oxide. Because they are not included among the seven UNFCCC-reportable gases or gas groups, the "other" fluorinated GHGs are not included in *Inventory* totals. However, their emissions are presented below because they often have high GWPs and large GWP-weighted emissions.

Total emissions of HFCs, PFCs, SF_6, and NF_3 from fluorochemical production are estimated to have increased from 32 MMT CO_2 Eq. (3,400 MT) in 1990 to a peak of 45 MMT CO_2 Eq. (5,700 MT) in 1999, declining to 3.9 MMT CO_2 Eq. (860 MT) in 2016[54] and rising again to 6.0 MMT CO_2 Eq. (1,200 MT) in 2022. These trends reflect estimated changes in fluorinated gas production and increasing use of control devices. Prior to 2000, only 2 facilities are known to have operated control devices to destroy fluorinated GHG emissions. After 2000, additional production facilities began to install and use control devices to destroy fluorinated GHG emissions,[55] and fluorinated GHG emissions declined sharply from 45 MMT CO_2 Eq. (5,700 MT) in 1999 to 13 MMT CO_2 Eq. (2,300 MT) in 2005. Emissions continued to fall more slowly through 2016, reflecting the installation of controls at an additional 4 facilities in 2011, 2012, 2015, and 2016. Total fluorinated GHG emissions rose from 2017 to 2022 as production increased at some facilities.

Emissions from the production of fluorochemicals other than HCFC-22 are reported under fluorochemical production (CRT category 2B9) in conjunction with emissions from HCFC-22 production described in Section 4.14 of this chapter.

HFC Emissions

Estimated emissions of HFCs increased from 8.7 MMT CO_2 Eq. in 1990 to a peak of 14 MMT CO_2 Eq. in 1999 (1,200 to 2,600 MT), declining with some fluctuation to 2.5 MMT CO_2 Eq. in 2022. Emissions in 1990 were primarily from facilities producing compounds other than saturated HFCs. The subsequent trends in emissions were driven by the growth in production of saturated HFCs and the imposition of controls. Production of saturated HFCs is estimated to have increased from around 0.3 MMT CO_2 Eq. (2,000 MT) in 1990 to over 300 MMT CO_2 Eq. (100,000 MT) by

[52] The totals presented below also include emissions from destruction of previously produced fluorinated GHGs that are shipped to production facilities for destruction, e.g., because they are found to be irretrievably contaminated.

[53] IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

[54] Emissions in MMT CO_2 Eq. were similar in 2017, but the 2017 emissions in MT were considerably higher (4,500 MT) due to anomalously high emissions of one low-GWP, unsaturated HFC at one facility.

[55] One facility is assumed to have installed controls in 2000, another installed controls in 2003, and three facilities are assumed to have installed controls in 2005.

2010 as HFCs replaced ozone-depleting substances, which were being phased out under the Montreal Protocol and Clean Air Act (EPA 2023a; EPA 2023b). This increase in HFC production drove HFC emissions to their 1999 peak. However, estimated emissions declined significantly from 1999 to 2005 due to the assumed addition of controls in 2000 and subsequent years. Estimated emissions of HFCs resumed their increase from 2005 to 2010, reaching 7.2 MMT CO_2 Eq. (2,300 MT), but again declined sharply in 2011 to 4.6 MMT CO_2 Eq. (1,200 MT) based on addition of controls. Since 2012, HFC emissions have continued to trend downward with some fluctuations, hitting a minimum of 1.7 MMT CO_2 Eq. in 2021. With the phase-out of production of saturated HFCs (Kigali Amendment, and U.S. AIM program), the downward trend of HFC emissions is expected to continue, but the share of HFC emissions that are not associated with saturated HFC production (approximately 0.7 MMT CO_2 Eq. in 2022) is likely to persist in the absence of additional controls.

PFC Emissions

Emissions of PFCs increased gradually from 18 MMT CO_2 Eq. (2,000 MT) in 1990 to 24 MMT CO_2 Eq. (2,800 MT) in 1999 but dropped to 4.0 MMT CO_2 Eq. (490 MT) by 2005, reflecting the addition of controls at high-emitting facilities and apparent changes to the mix of products produced at another facility.[56] Overall PFC emissions from 2005 to 2022 have remained relatively steady, oscillating around 2.5 MMT CO_2 Eq. The upward trend between 1990 and 1999 was largely driven by the three facilities that reported their historical emissions to the EPA. In the absence of historical emissions data for other facilities, the quantities of fluorinated GHGs produced or transformed at other facilities emitting PFCs are estimated to have remained generally steady between 1990 and 2009 and therefore do not contribute to the emissions trend before 2010. For most of the fluorinated GHGs produced at these facilities, there was no available industry information to inform activity estimates or trends for 1990 to 2009. Therefore, as discussed in the Methodology section below, 2010 production values from EPA's GHGRP were assumed to have held constant for these compounds from 1990 to 2010.

SF_6 Emissions

Emissions of SF_6 are estimated to have risen gradually from 5.8 MMT CO_2 Eq. (250 MT) in 1990 to a peak of 7.5 MMT CO_2 Eq. (320 MT) in 1995, to have declined slowly to 7.0 MMT CO_2 Eq. in 2000, and then to have declined more rapidly to a minimum of 0.0004 MMT CO_2 Eq. (0.01 MT) in 2017, after which emissions rose and fluctuated between 0.056 MMT CO_2 Eq. (in 2020) and 0.0024 MMT CO_2 Eq. (in 2022). The rapid emissions decline after 2000 was driven first by the imposition of controls at one facility and then by the cessation of production in 2010 at a major U.S. SF_6-producing facility.

NF_3 Emissions

Since 1990, estimated emissions of NF_3 have fluctuated between 0.11 MMT CO_2 Eq. and 0.72 MMT CO_2 Eq., with peaks occurring in 2000 (0.71 MMT CO_2 Eq.), 2010 (0.70 MMT CO_2 Eq.), and 2020 (0.72 MMT CO_2 Eq.), and lows occurring in 1990 (0.29 MMT CO_2 Eq.), 2003 (0.33 MMT CO_2 Eq.), and 2018 (0.11 MMT CO_2 Eq.). NF_3 may be emitted both from the production of NF_3 and from the production of other fluorochemicals. The dominant source since 2010 has been production of NF_3. Trends after 2010 were driven by changes both in NF_3 production and in

[56] In a summary of 1990 through 2010 emissions submitted to EPA (described more below), 3M, which owns several facilities that historically emitted PFCs, noted that the mix of products produced at its various facilities had changed over time, leading to changes in the magnitude and contents of emissions. This change in magnitude and contents was particularly pronounced at 3M's Decatur facility (referred to elsewhere in this document as "3M Company"), where emissions declined from 15.8 MMT CO_2 Eq. in 2000 to 0.53 MMT CO_2 Eq. in 2002, and where the contents of emissions changed from HFCs, PFCs, SF_6 and other fluorinated GHGs in 2000 to PFCs and other fluorinated GHGs in 2003. (Emissions in 2002 were not differentiated by group). Emissions were also reduced after the installation of a control device at the Cordova facility. 3M noted that Initial start-up of the thermal oxidizer occurred in 2003, but that it took time to optimize the operation of the thermal oxidizer and treatment of the various gas streams, leading to a decrease in emissions over several years.

the emission rate (kg NF_3 emitted/kg NF_3 produced) for NF_3 production, with both contributing to increased emissions since 2018. For 1990 through 2009, the NF_3 that is emitted from the production of NF_3 is assumed to be influenced by the trajectory of NF_3 production, which is generally assumed to follow production trends in the semiconductor industry except where NF_3 facility capacity limits production further. Semiconductor production increased steadily from 1995 to 2007 but is estimated to have declined from 2007 through 2010. As described in the Methodology section under "Estimated Emissions for 3M facilities," the NF_3 that is emitted from production of other fluorochemicals is assumed to have been emitted as a constant fraction of the "other" fluorinated GHGs whose 1990 through 2010 emissions were reported by 3M facilities. This fraction was estimated based on the fraction of "other" fluorinated GHG emissions accounted for by NF_3 between 2011 and 2015 and is highly uncertain. Nevertheless, because the highest-emitting 3M facilities reported decreasing emissions of all other fluorinated GHG groups between 2000 and 2005 (due to the installation of a control device at one facility and apparent production changes at another), NF_3 emissions also appear likely to have decreased during this period.

Other Fluorinated GHG Emissions

Other fluorinated GHGs, i.e., those not included in the UNFCCC-reportable gases or gas groups, are also emitted in significant quantities from fluorinated gas production and transformation processes. Estimated emissions of these other fluorinated GHGs are provided in Table 4-64 for the years 1990, 2005, and the period 2018 to 2022. The other fluorinated GHGs with the highest estimated emissions in 2022 are presented separately, and the remaining other fluorinated GHGs are aggregated.

Total emissions of other fluorinated GHGs increased from 4.7 MMT CO_2 Eq. (450 MT) in 1990 to a peak of 10.1 MMT CO_2 (870 MT) in 2000, declining rapidly to 0.90 MMT CO_2 Eq. in 2009 and then declining more slowly to 0.13 MMT CO_2 Eq. (40 MT) in 2021 and 2022. Between 1990 and 2009, estimated emissions of other fluorinated GHGs were primarily driven by the emissions reported by 3M facilities, which showed significant declines between 2000 and 2005, reflecting apparent production changes at one facility and the installation of a control device at another. The decline in emissions from 2019 to 2020 was due to a decrease in the emission rate at one facility.

Table 4-63: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	6.7	1.7	1.3	1.1	0.9	0.7	1.0
HFC-125	0.1	1.9	0.4	0.4	0.4	0.4	0.3
HFC-143a	0.1	0.8	0.7	0.6	0.3	0.2	0.3
HFC-134a	+	0.4	0.3	0.3	0.2	0.2	0.3
1H,4H-Perfluorobutane	0.0	0.0	0.0	+	+	+	0.2
1H,6H-Perfluorohexane	0.0	0.0	0.0	+	+	+	0.2
Other HFCs	1.6	0.5	0.2	0.2	0.2	0.2	0.3
Perfluorocyclobutane	11.2	0.7	1.3	1.4	1.1	1.3	1.3
PFC-14 (Perfluoromethane)	2.4	1.4	1.0	0.9	0.9	0.9	1.0
Other PFCs	3.9	1.9	0.7	0.7	0.4	0.4	0.6
Nitrogen trifluoride	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Sulfur hexafluoride	5.8	3.3	+	+	+	+	+
Total	**32.3**	**13.2**	**5.9**	**6.2**	**5.2**	**4.9**	**5.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Table does not sum due to independent rounding.

Table 4-64: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	540	140	100	89	71	56	77
HFC-125	43	600	130	130	120	110	105
HFC-143a	30	160	160	120	63	49	57
HFC-134a	37	340	200	220	180	180	190
1H,4H-Perfluorobutane	0	0	0	1.2	0.60	1.2	53
1H,6H-Perfluorohexane	0	0	0	0.92	0.47	0.90	41
Other HFCs	500	400	270	260	230	250	270
Perfluorocyclobutane	1,200	70	130	150	120	130	140
PFC-14 (Perfluoromethane)	360	210	150	130	140	140	160
Other PFCs	420	210	71	77	41	49	59
Nitrogen trifluoride	18	37	6.7	35	45	31	31
Sulfur hexafluoride	250	140	0.15	0.17	0.24	0.21	0.10
Total HFCs, PFCs, SF_6, and NF_3	**3,400**	**2,300**	**1,200**	**1,200**	**1,000**	**1,000**	**1,200**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-65: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	2.4	1.9	+	0.1	+	+	+
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	+	+	+	+	+	+	+
Trifluoromethyl sulphur pentafluoride	1.2	0.9	+	0.1	+	+	+
Hexafluoropropylene oxide	0.3	0.3	0.3	0.3	+	+	+
FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	+	+	+
Others	0.8	0.5	0.1	0.1	0.1	+	+
Total Other Fluorinated GHGs	**4.7**	**3.7**	**0.6**	**0.6**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-66: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	170	140	4	4	2	1	2
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	6	4	5	6	3	6	3
Trifluoromethyl sulphur pentafluoride	66	53	3	4	1	1	1
Hexafluoropropylene oxide	34	34	32	32	2	2	2

FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	1	1	1
Others	170	120	76	84	35	33	35
Total Other Fluorinated GHGs	450	350	120	130	43	43	45

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-67: Production and Transformation of Fluorinated GHGs (kt)[a]

Set of Facilities	1990	2005	2018	2019	2020	2021	2022
Facilities reporting their F-GHG emissions, production, and transformation to GHGRP after 2010[b]	86	271	376	371	352	348	370
Facilities reporting only their F-GHG production and transformation to GHGRP after 2010	3.3	3.3	11.2	9.7	8.2	7.5	11.2
Total Production and Transformation	89	274	387	381	360	356	381

[a] Totals are presented across species to protect confidential business information.

[b] Includes 1 facility that reported production, but not emissions, of SF_6 through 2010.

Note: Tables may not sum due to independent rounding.

Methodology

The *2006 IPCC Guidelines* as elaborated by the 2019 Refinement include Tier 1, Tier 2, and Tier 3 methods for estimating fluorinated GHG emissions from production of fluorinated compounds. The Tier 1 method calculates emissions by multiplying a default emission factor by total production. Specific default emission factors exist for production of SF_6 and NF_3; a more general default emission factor covers production of all other fluorinated GHGs. (The more general default emission factor was developed based on data from U.S. facilities collected under the GHGRP between 2011 and 2016.) The Tier 2 method calculates emissions using a mass-balance approach. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of fluorinated GHGs emitted from process vents, leaks, container venting, and other sources, considering any abatement technology. The Tier 3 method is often implemented by developing and applying facility-specific emission factors indexed to production.

Based on available data on emissions and activity, EPA used a form of the IPCC Tier 3 method to estimate fluorinated GHG emissions from most U.S. production of fluorinated compounds. Emissions from U.S. production for which there are fewer data are based on the Tier 1 method.

Overview of GHGRP Data for this Source Category

As discussed further below, much of the data used to develop the estimates presented here come from the GHGRP. The data were collected under two sections of the GHGRP regulation—Subpart L, Fluorinated Gas Production; and Subpart OO, Suppliers of Industrial Greenhouse Gases. Under Subpart L, certain fluorinated gas production facilities must report their emissions from a range of processes and sources, detailed further below. Data collected under Subpart L include emissions data for calendar years 2011 through 2022. Under Subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export. Data collected under Subpart OO include production and transformation data for calendar years 2010 through 2022. Facilities' production and transformation data are not shown here because they are considered confidential business information under the GHGRP.

Emissions Reported Under Subpart L of the GHGRP

Under Subpart L, facilities that produce a fluorinated gas must report their greenhouse gas emissions if the facility emits 25,000 MT CO_2 Eq. or more per year in combined emissions from fluorinated gas production, stationary fuel combustion units, miscellaneous uses of carbonate, and all other applicable source categories listed in the rule. (For purposes of calculating emissions from fluorinated gas production for inclusion in the total that is compared to the threshold, emissions are assumed to be uncontrolled.) Facilities must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks.

Under the GHGRP, "fluorinated GHGs," whose emissions must be reported, include SF_6, NF_3, and any fluorocarbon except for substances with vapor pressures below 1 Torr at 25 degrees C and substances that are regulated as "controlled substances" under EPA's ozone-protection regulations at 40 CFR Part 82, Subpart A (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and halons). In addition to SF_6 and NF_3, this definition includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroethers (HFEs), fully fluorinated tertiary amines, perfluoropolyethers (including PFPMIE), and hydrofluoropolyethers, and others. "Fluorinated gases," from whose production or transformation emissions must be reported, include the fluorinated GHGs detailed above as well as CFCs and HCFCs.[57]

Facilities calculate emissions from process vents using one of two methods. For vents that emit 10,000 MT CO_2 Eq. or more (considering controls) of fluorinated GHGs from continuous processes, facilities must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use measurements, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions.

To calculate emissions from equipment leaks, facilities that report under Subpart L are required to collect information on the number and type of pieces of equipment; service of each piece of equipment; concentration of each fluorinated GHG in the stream; and the time period each piece of equipment was in service. Facilities use one or more of the following methods to calculate emissions from equipment leaks (EPA 1995):

- Average Emission Factor Approach in EPA Protocol for Equipment Leak Estimates.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with EPA Method 21.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with site-specific leak detection methods.
- Site-specific leak detection methods.

Most emissions are reported by chemical; the exceptions are (1) fluorinated GHGs that are emitted in quantities of 1,000 MT CO_2 Eq. or less across all production and transformation processes at a facility and (2) fluorinated GHGs that are emitted from facilities that produce only one fluorinated GHG, where the emitted fluorinated GHG is not the fluorinated gas produced. In these cases, the emissions are reported in CO_2 Eq. by fluorinated GHG group. There are 12 fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behavior, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and SF_6, saturated HFCs with two or fewer hydrogen-carbon bonds, saturated HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, and others (see Table 4-68 for a full list).

[57] HCFC-22 is considered a fluorinated gas under the GHGRP, but emissions from HCFC-22 production are reported separately from emissions from production of other fluorinated gases.

Table 4-68: Fluorinated GHG Groups Under Which Certain Emissions Are Reported Under Subpart L of the GHGRP and Associated GWPs

Fluorinated GHG Group	GHGRP Default Global Warming Potential (100-yr.)
Fully fluorinated GHGs	10,000
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	3,700
Saturated HFCs with 3 or more carbon-hydrogen bonds	930
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	5,700
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	2,600
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	270
Fluorinated formates	350
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	30
Unsaturated PFCs, unsaturated HFCs, unsaturated HCFCs, unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	1
Fluorotelomer alcohols	1
Fluorinated GHGs with carbon-iodine bond(s)	1
Other fluorinated GHGs	2,000

Two other datasets reported under Subpart L are relevant to estimating uncontrolled emission factors. (As discussed further below, such uncontrolled emission factors are applied to years before Subpart L reporting began (for CY 2011) and before emission controls were put into place.) First, in addition to reporting emissions by chemical at the facility level, facilities report emissions from each production and transformation process at the facility in tons of CO_2 Eq. by fluorinated GHG group. To calculate CO_2 Eq. emissions, facilities use a chemical-specific 100-year GWP where one is available for the compound of interest. If no chemical-specific 100-year GWP is available for the compound of interest, facilities use the GHGRP default GWP for the fluorinated GHG group of which the compound is a member. These default GWPs are shown in Table 4-63.

Second, for each process, facilities also report the extent to which emissions are abated (the effective destruction efficiency or EDE) as a range. The EDE is calculated as follows:

$$EDE = 1 - \frac{CE_{PV}}{UE_{PV}}$$

where:

EDE = Effective destruction efficiency of the process

CE_{PV} = Actual GWP-weighted controlled emissions from all vents for the process, MT CO_2 Eq.

UE_{PV} = Hypothetical GWP-weighted uncontrolled emissions from all vents for the process, MT CO_2 Eq. (CE_{PV} will equal UE_{PV} if the process is not controlled, resulting in a calculated EDE of 0).

Note that the EDE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the EDE calculation. Table 4-69 provides the EDE ranges available for facilities to report and the arithmetic means of each range. The use of these datasets to calculate uncontrolled emission factors is discussed in more detail in the "1990-2010 Emissions Estimates" section below.

Verification of GHGRP Reports

Data reported under the GHGRP, including emissions and production, are electronically verified using range checks, internal consistency checks, and time-series consistency checks. Where the data fail a preliminary check, EPA contacts the facility to see whether there is an explanation for the issue or whether the data are indeed erroneous. In the latter case, facilities are required to correct the data. Where one or more of the anomalous data elements is not explained or corrected, the report for that facility for that year is considered unverified.

1990-2010 Emissions Estimates

For 14 of the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under "2011-2022 Emissions" below, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, i.e., activity data, and (3) reported and estimated levels of emissions control at each facility in each year. (For the other 3 fluorinated ga production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions were estimated using data submitted by the company, as explained further below.)

Facility- and Chemical-Specific Emission Factors Reflecting Emissions Controls

Facility- and chemical-specific emission factors were developed based on the 2011 to 2015 emissions reported under the GHGRP (discussed above) and the 2011 to 2015 production and transformation of fluorinated GHGs reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period.[58] As discussed further below in the Uncertainty section, emissions of any particular fluorinated GHG are likely to occur only from a subset of the production or transformation processes at each facility, but in the absence of information on chemical-specific emissions at the process level, it was assumed that all fluorinated GHG production and transformation processes at the facility emit all fluorinated GHGs at the facility. This yielded the emission factors for each fluorinated GHG at each facility. Both emissions and activity (production + transformation) totals were summed over the five-year period to account for the intermittent and variable nature of some emissions and production/transformation processes. Compounds that were not emitted or produced/transformed between 2011 and 2015 but that were emitted or produced/transformed later were assumed not to have been emitted or produced/transformed (as applicable) before 2011.

Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls

The 2011 to 2015 emissions reported under the GHGRP reflect emissions controls to the extent those are implemented at each facility. Because facilities have not always controlled their fluorinated GHG emissions since 1990, uncontrolled emission factors were developed for each facility to apply to years when the facility's emissions were not believed to be controlled. To estimate uncontrolled emissions, GHGRP data were first used to assess the 2011 to 2015 levels of control for each production or transformation process at each facility.

To calculate uncontrolled emissions from each process and fluorinated GHG group, a point estimate of the effective destruction efficiency (EDE, described above) was required and was estimated using the arithmetic mean

[58] Permit data for two facilities indicated that they began controlling emissions at some point between 2011 and 2015. However, the actual emissions reported by these facilities did not change substantially after the date when the permit indicated that controls were imposed. For this reason, the reported 2011 to 2015 emissions and emission factors are believed to be representative of emissions for these facilities before 2011.

of the lower and upper bounds of the EDE range reported for the process.[59] This was consistent with the approach taken in the *2019 Refinement* to develop the Tier 1 factor for fluorinated gas production facilities. The reported vented emissions for each process and fluorinated GHG group were divided by (1 - arithmetic mean EDE) to obtain the estimated uncontrolled emissions from process vents for that process and fluorinated GHG group. For each fluorinated GHG group, the controlled emissions across processes (including emissions from both vents and leaks) and the uncontrolled emissions across processes (including emissions from both vents and leaks) were then summed, and the first was divided by the second. This yielded an average level of control for each fluorinated GHG group at each facility. All fluorinated GHGs within each fluorinated GHG group at each facility were assumed to be controlled to the same level. To estimate the uncontrolled emissions of each fluorinated GHG within each group at each facility, the emissions of each fluorinated GHG were divided by the level of control estimated for its fluorinated GHG group at the facility. The same procedure was used to estimate uncontrolled emission factors as had been used to estimate controlled emission factors: the estimated uncontrolled 2011 to 2015 emissions of each fluorinated GHG were summed, and this sum was divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility from 2011 to 2015.

Table 4-69: Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes

DE ranges	Lower Bound	Upper Bound	Arithmetic Mean of Bounds
>=0% to <75%	0.0	0.75	0.375
>=75% to <95%	0.75	0.95	0.85
>=95% to <99%	0.95	0.99	0.97
>=99%	0.99	0.9999	0.995

Estimated Levels of Emissions Controls

As discussed above, both uncontrolled emission factors and controlled emission factors were developed for each facility and fluorinated GHG; these emission factors were developed for estimating emissions from production and transformation processes for years 1990 to 2010. The following information and assumptions were used to determine whether and when emissions from facilities were likely to have been controlled from 1990 to 2010. For the estimated status of emissions controls at each facility reporting under Subpart L, and, where relevant, the starting year for those controls, see Table 4-70.

- Facilities with publicly available information on the presence and use of control devices were assumed to control their emissions starting in the year specified in the publicly available information. Publicly available information included operating permits, news articles on facility modifications, company press releases, etc. Where the publicly available information documents that a control device was in place beginning in a certain year, the facility was assumed to control process emissions beginning in that year, and the controlled emission factor was used in estimating emissions for that year and the following years. The uncontrolled emission factor was used to estimate emissions in earlier years.
- In the absence of other control information, facilities that never reported DRE ranges other than ">=0% to <75%" for their production and transformation processes during reporting years 2011 and 2012 were assumed to have no control devices in place during the time period 1990 to 2012.
- Facilities that reported DRE ranges other than ">=0% to <75%" for at least one production or transformation process for 2011 or 2012 but for which other control information was not available were assumed to have begun controlling their emissions in 2005.

[59] Note that facilities would report a range of 0% to 75% even if they do not abate emissions at all; thus, the assumption that emissions are 37.5 percent controlled may overestimate the hypothetical uncontrolled emissions of some facilities, e.g., those that do not abate any emissions.

Table 4-70: Estimated Starting Years for Emission Controls at Each Fluorinated Gas Production Facility Reporting under Subpart L of the GHGRP

Facility Name	Estimated Start Year	Basis of Estimation
3M COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
3M CORDOVA	2003	Climate News Article[60]
3M Cottage Grove Center - Site	2016	Reported a DRE range other than ">=0% to <75%" for the first time in 2016
Airgas Therapeutics LLC - Scott Medical Products	No controls	Never reported a DRE range other than ">=0% to <75%"
ANDERSON DEVELOPMENT COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
ARKEMA, INC.	2005	Reported a DRE range other than ">=0% to <75%" in 2011
Chemours - Corpus Christi Plant	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS CHAMBERS WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS COMPANY - FAYETTEVILLE WORKS	2015	Reported a DRE range other than ">=0% to <75%" for the first time in 2015
CHEMOURS EL DORADO	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS LOUISVILLE WORKS	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS WASHINGTON WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
DAIKIN AMERICA INC.	1993	Title V operating permit[61]
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	2012	Title V operating permit[62]
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	2011	Title V operating permit[63]
Honeywell Metropolis	No controls	Never reported a DRE range other than ">=0% to <75%" (did not report under Subpart L)
MEXICHEM FLUOR INC.	1993	Title V operating permit[64]
Versum Materials US, LLC	No controls	Never reported a DRE range other than ">=0% to <75%"

Activity Data

The activity data for production and transformation of fluorinated compounds for 1990 to 2010 are based on production and transformation data reported to EPA by certain facilities for certain years, on production capacity data, and on fluorinated GHG production and consumption trends estimated for the various fluorinated GHG-consuming industries.

Production and Production Capacity Data

Production data are available from reporting to the U.S. GHGRP under Subpart OO, Suppliers of Industrial Greenhouse Gases, and from an industry survey conducted by U.S. EPA in 2008 and 2009. Production and transformation data were reported under Subpart OO for 2010 and later years. The responses to the industry survey included production data for certain fluorinated gases at certain facilities for the years 2004, 2005, and

[60] See https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

[61] Daikin (2013) http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0.

[62] Honeywell (2011) https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

[63] Honeywell (2012) https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

[64] See https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

2006. 2004 to 2006 production data are available for 15 fluorinated compounds. Year 2006 production at an SF_6-producing facility was estimated based on production capacity data as described below (Rand 2007). Production of certain compounds at one other facility was estimated based on 2003 production capacity estimates from SRI 2004.

Estimated Production

Estimated production for facilities and fluorinated GHGs for which production or production capacity data were available for some years before 2010.

For facilities and fluorinated GHGs for which production or production capacity data were available for 2006 or 2003, production between 2006 or 2003 (as applicable) and 2010 (or 2011) was estimated by interpolating between the 2006 production or 2003 production capacity value and the 2010 (or 2011) production value reported under Subpart OO.

For the years before the earliest year with production or production capacity data (e.g., years 1990 to 2002 or 2003), production was estimated based on growth or consumption trends for the major industries using each fluorinated GHG.

- For fluorinated compounds that are commonly emitted in the semiconductor industry, estimates of U.S. layer-weighted semiconductor production (Total Manufactured Layer Area, or TMLA) were used to inform the fluorinated compound production estimates (EPA 2023c). Fluorinated compound production values were assumed to vary with TMLA from 1990 to 2002 or 2003. For example, 1998 production of PFC-14 at a particular facility was estimated by multiplying the 2003 production of PFC-14 at that facility by the ratio between the TMLA estimated for 1998 and the TMLA estimated for 2003. Fluorinated compounds for which TMLA was used to estimate production include PFC-14, PFC-116, PFC-218, perfluorocyclobutane (c-C_4F_8), and NF_3. (Note that the TMLA data were also extrapolated from year 1995 to 1990 based on the average change per year from 1995 to 2009.)

- SF_6 is commonly used in electric power systems, magnesium production, and electronics manufacturing. SF_6 consumption estimates across these three industries for 1990 to 2003 were used to inform the SF_6 production data (EPA 2023d); SF_6 production was assumed to vary with consumption totals from 1990 to 2003.

- For HFCs commonly used as replacements for ozone-depleting substances (ODS), such as HFCs used as substitutes for CFCs and HCFCs in air-conditioning and refrigeration equipment, HFC production data for certain fluorinated compounds from the Vintaging Model (VM) were used to inform the HFC production estimates (EPA 2023b). HFC production values were assumed to vary with the VM estimates of production. The industry trend data were applied to the list of HFCs in Table 4-71.

Table 4-71: List of Saturated HFCs, Unsaturated HFCs (Hydrofluoroolefins or HFOs), and Unsaturated HCFCs (Hydrochlorofluoroolefins or HCFOs) whose 1990-2009 Production Was Estimated Using Vintaging Model, Virgin Manufacturing by Chemical

Fluorinated Gas
HFC-23
HFC-32
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-236fa
HFC-245fa
HFC-365mfc
HCFO-1233zd(E)
HFO-1234yf
HFO-1234ze
HFO-1336mzz(Z)
HFC-4310mee

Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available.

In the absence of production data for the period 1990 to 2009, the production data reported to the GHGRP under Subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series.

In both cases, 2009 production was estimated by conducting a trend analysis on the Subpart OO production data for years 2010 to 2015. In instances where there did not appear to be a trend, the average of the production values for years 2010 to 2015 was used as the estimated production for year 2009. In instances where there was a trend, the year 2010 (or 2011) production value was used as the estimated production for year 2009.

If the industry trend information discussed above was applicable to a fluorinated compound, it was assumed that production varied with the industry trend from 1990 to 2009. If no industry trend information was available, it was assumed that production from 1990 to 2008 remained constant at the 2009 value.

For facilities and fluorinated compounds where information was available on annual production capacity, the estimated activity data was reviewed and compared to the known production capacity. For instances where the estimated activity data exceeded known production capacity for a certain year, the production estimate was set equal to the capacity value. In addition, where information was available on the starting year for production of a fluorinated GHG at a facility, production was only estimated beginning in the process startup year through 2009.

Estimated Emissions for 3M Facilities

3M provided 1990, 1995, 2000, and 2002 through 2010 emissions data for three facilities: 3M Cordova, 3M Company, and 3M Cottage Grove Center - Site.[65] Therefore, speciated 1990-2010 emissions at these facilities were estimated using a different methodology than that described above.[66]

[65] For 1990, 1995, and 2000, 3M provided emissions data for a Pilot Development Center in addition to the other three facilities. Emissions by group from the Pilot Development Center were added to and are represented by the emissions by group for 3M Cottage Grove Center – Site.

[66] 3M's methods for estimating its emissions are described in detail in "3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions," February 2024 (3M, 2024). In brief, 3M estimated emissions from its processes using

3M emissions data were provided by facility and by fluorinated GHG group in metric tons of CO_2 Eq., weighted by 100-year GWPs from various IPCC Assessment Reports. The fluorinated GHG groups included HFCs, PFCs, SF_6, HFEs, and other fluorinated GHGs. (3M noted that the "other fluorinated GHG" category included NF_3.) GWPs from the IPCC *Third Assessment Report* (TAR) were used to report totals for 1990, 1995, 2000, and 2003 to 2006. GWPs from the IPCC *Fifth Assessment Report* (AR5) was used to report totals for 2002, and GWPs from the IPCC *Fourth Assessment Report* (AR4) were used to report totals for 2007 to 2010. The emissions were also categorized as emissions from electrochemical fluorination (ECF) processes and downstream (DS) emissions. The DS emissions for 1990, 1995, and 2000 were reported as a total for each facility rather than by fluorinated GHG group.

To present emissions estimates by compound, EPA needed to disaggregate the data provided by 3M. The first step was to disaggregate the 1990, 1995, and 2000 DS emissions into fluorinated GHG groups. Since the 2003 to 2006 data were calculated using the same set of GWPs as the 1990, 1995, and 2000 data, the DS emissions of each group at each facility for 2003 to 2006 were divided by the total DS 2003 to 2006 emissions at that facility to obtain a set of fractions. These fractions were then multiplied by the 1990, 1995, and 2000 DS totals to sort those emissions into groups.

For 2002, ECF and DS emissions were only reported under the PFC group. (3M noted that chemical classifications were not preserved when 2002 emissions were recalculated using GWP values from AR5.) Since data for every other year showed emissions reported from multiple fluorinated GHG groups, and since 2004 was the closest year with emissions well sorted into fluorinated GHG groups, the ECF and DS emissions for 2002 were separated into multiple fluorinated GHG groups using the 2004 ECF and DS groups shares for each facility.

The next step was to disaggregate the emissions of each fluorinated GHG group into emissions of the relevant compounds in that group. To accomplish this, EPA assumed that emissions of each fluorinated GHG group before 2011 consisted of the same fluorinated GHGs, in the same proportions, as from 2011 through 2015. However, each compound's share of the GWP-weighted emissions of the group in a given year depends on the GWPs used for that compound and for the other compounds in the group in that year. To account for this, EPA multiplied the reported 2011 to 2015 emissions of each compound in metric tons by the corresponding GWPs for that compound from the TAR, AR4, and AR5 to generate three sets of emissions by compound in metric tons of CO_2 Eq. For each set, the sum of emissions across 2011 to 2015 for each compound were divided by the total emissions for the corresponding fluorinated GHG group for those five years to calculate shares for each group.

The 3M emissions data by group for 1990, 1995, 2000, and 2002 to 2010 were then speciated by compound using the appropriate set of share values for each year. Since 3M Company only reported emissions of one compound in 2011 to 2015 but had emissions from multiple fluorinated GHG groups in 1990, 1995, 2000, and 2002 to 2010, the share values for 3M Cordova were used to speciate the 1990, 1995, 2000, and 2002-2010 emissions by group for 3M COMPANY. The speciated emissions in metric tons of CO_2 Eq. by compound for each facility were then divided by the appropriate TAR, AR4, or AR5 GWP for each compound to obtain the estimated emissions in metric tons of each compound for 1990, 1995, 2000, and 2002 to 2010.

Linear interpolation was then used to estimate emissions for 1991 to 1994, 1996 to 1999, and 2001 for each compound for these three facilities.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

There is a subset of facilities that report production and transformation of fluorinated gases under Subpart OO and that also have emission levels less than the threshold value for reporting under Subpart L (i.e., uncontrolled emissions below the 25,000-MT CO_2 Eq. threshold). For these facilities, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the

emission factors that were developed using methods similar to those used for developing emission factors under the GHGRP. As under the GHGRP, emission factors were multiplied by different types of activity data (e.g., production) to estimate emissions for each facility and year. In 2003 and later years, 3M also accounted for emission reductions attributable to operation of the thermal oxidizer at the Cordova plant.

specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table. Emissions are assumed to have been flat at the 2010 value in the years before 2010.

Estimated Emissions for SF_6 Production Facility

For an SF_6 production facility that ceased production in 2010, the year before emissions from fluorinated gas production were required to be reported under the GHGRP, SF_6 emissions were estimated using historical production capacity, the global growth rate of SF_6 sales reported in RAND 2007, and the Tier 1 default emission factor for production of SF_6 in the 2019 Refinement. For this plant, a 1982 SF_6 production capacity of 1,200 short tons (Perkins 1982) was multiplied by the ratio between the RAND survey SF_6 sales totals for 2006 and 1982, 1.52 (RAND 2007), resulting in estimated production of 1,652 metric tons in 2006. This production was assumed to have declined linearly to zero in 2011.

2011-2022 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 2011 to 2022 emissions are estimated using the fluorinated GHG emissions reported under Subpart L of the GHGRP.

As discussed above, most emissions reported under Subpart L are reported by chemical, but some emissions are reported only by fluorinated GHG group in MT CO_2 Eq. Between 2011 and 2022, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group has ranged between 1 and 2 percent. In this analysis, to ensure that all emissions are reported by species, emissions that are reported only by fluorinated GHG group are assumed to consist of the fluorinated GHGs in that group that are reported by chemical at the facility. As discussed further in the Uncertainty section, this is likely to result in incorrect speciation of some emissions, but the impact of this incorrect speciation is expected to be small.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

As discussed above, for facilities that produce fluorinated GHGs but that do not report their emissions under subpart L, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table.

Uncertainty

The estimates in this memo are subject to a number of uncertainties. These uncertainties are generally greater for years before 2011, when reporting of fluorinated GHG emissions from fluorinated gas production began under the GHGRP, than for 2011 and following years. However, the emissions estimated from 2011 to 2022 are also subject to various uncertainties. The uncertainties for both the 1990 to 2010 and 2011 to 2022 periods are discussed in more detail below.

1990-2010 Uncertainty

The uncertainty of emissions estimated for 1990 through 2010 is considerably greater than that for emissions for 2011 through 2022 because emissions were not reported under the GHGRP. EPA has estimated emissions using estimated emission rates, fluorochemical production and transformation activity, and levels of control, and each set of estimates is subject to uncertainty.

Uncertainty regarding activity data

Identity of emitting processes

In reality, emissions of particular fluorinated GHGs are linked to production and/or transformation of particular fluorinated gases at facilities. However, GHGRP information/data does not link emissions of specific fluorinated GHGs to production or transformation of specific fluorinated gases. For the estimates presented here, therefore, all emissions are indexed to total production across all fluorinated gases. This may not capture trends in emissions that are driven by trends in production or transformation of subsets of the fluorinated gases produced at a facility.

Produced and emitted gases change over time

The set of gases produced at a facility, and therefore the set of fluorinated GHGs that are emitted by that facility, may change over time. It is likely that certain production and transformation processes that existed from 2011 to 2015 (the basis of the emission factors used to back-cast emissions in this analysis) did not exist throughout the entire previous time series (1990 to 2010). In such cases, emissions of the fluorinated GHGs emitted from the new processes will be overestimated by this analysis for certain years before 2011. On the other hand, it is also likely that some production and transformation processes, and their associated fluorinated GHG emissions, occurred only during the 1990 to 2010 period and not later, meaning that their emissions are not represented in the emission factors developed based on the 2011 to 2015 emissions and production data collected under the GHGRP. Such emissions will therefore not be captured by this analysis. The most prominent example of the second situation is probably production of CFCs and HCFCs other than HCFC-22 between 1990 and 2009, which has declined steadily since 1990 as the production of CFCs and HCFCs for emissive uses has been phased out under the Montreal Protocol and Clean Air Act. Production of CFCs and HCFCs can sometimes result in emissions of HFCs or PFCs.

Quantity of produced gases

Where production or production capacity data were available for certain fluorinated gases, facilities, and years before 2010, those data were incorporated into this analysis. However, even for facilities and compounds for which data were available in certain years, there were several years for which data were not available. For multiple produced compounds, data were available only in 2010. To estimate trends in production of compounds for years before production or production capacity data were available, production of certain compounds was indexed to known national production or consumption trends for those compounds. This is the case for most HFCs, several PFCs, SF_6, and NF_3. National production estimates are available for HFCs, increasing confidence in country-level production estimates, but the distribution of production among the various HFC-producing facilities is uncertain. Where estimated production was indexed to consumption (for several PFCs, SF_6, and NF_3), the uncertainty is larger than for HFCs because changes in net imports/exports (which are not known) may also affect the production trend.

For certain fluorinated gases, trend information was not available; therefore, production was back-cast by assuming that it had remained constant at the 2010 level from 1990 through 2009. This is a highly uncertain assumption.

Some production and transformation activity is not reported under Subpart OO or modeled in back-casting

Under Subpart OO, quantities of fluorinated GHGs that are produced and transformed at the same facility are not reported to us, although any emissions from such processes are reported under Subpart L. Such unreported production and transformation are therefore not captured in the 1990 to 2010 activity estimates used to estimate 1990 through 2010 emissions. To the extent that such unreported production and transformation drive emissions and change over time, the trends will not be captured by this analysis.

Facilities that no longer produce fluorinated gases or that started producing them after 1990

Some facilities may have produced fluorinated gases at some point between 1990 and 2010 that no longer produced those compounds after 2010. One SF_6 producer is known to fall into this category and its 1990 to 2010 emissions were estimated, but there may be other facilities that are not included in this analysis. On the other hand, some facilities for which 1990 to 2010 emissions were estimated may not have produced them over the

entire time series, in which case emissions of the compounds those facilities are assumed to have emitted could be overestimated.

Uncertainty regarding emission factors

Emission rates change over time

The emission factors used to estimate 1990 to 2010 emissions are based on the emissions and production reported from 2011 to 2015, reflecting emission rates during that period. For processes that have been used throughout the timeseries, emission rates may have changed over time as the process was optimized to increase efficiency, decreasing by-product emissions, or alternatively, as the process was optimized to maximize production, which sometimes increases by-product emissions. Emission rates also depend on the extent to which emissions are controlled at the facility, the uncertainties for which are discussed further below.

Emissions from container venting and destruction may not scale with production

In this analysis, emissions from container venting and destruction of previously produced fluorinated GHGs were included in the emission factors used to estimate 1990 to 2010 emissions. This implicitly assumes that such emissions scale with production and transformation. While this seems likely to be broadly true, there may be exceptions. However, since emissions from container venting and destruction are generally a small share of facility emissions (2 percent, on average), the impact of such exceptions is expected to be small.

Uncertainty regarding levels of control

In this analysis, the arithmetic mean of the DRE range reported by each facility for each process was used to estimate the DRE for that process and the uncontrolled emissions for that process. Since the emissions implied by the bounds of each DRE range span at least a factor of four,[67] this is an uncertain assumption. The uncertainty is mitigated somewhat by the fact that there are generally several processes at each facility, meaning that departures from the assumed mean average out to some extent. There is also uncertainty in the assumptions that (1) all fluorinated GHGS within a particular fluorinated GHG group are abated to the same extent and (2) facilities for which control device start dates are unavailable began to control emissions in 2005.

Quantitative uncertainty estimate for uncontrolled emission factors from *2019 Refinement*

As noted above, 2011 to 2016 data from the GHGRP was used to develop the Tier 1 default uncontrolled emission factor for the *2019 Refinement*, using methods similar to those described here. A Monte Carlo analysis performed to assess the uncertainty of the Tier 1 default factor indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent. This uncertainty estimate considered the uncertainty regarding the levels of control, but not the uncertainty of applying factors from one time period at the facility to much earlier time period (although the variability of each facility's emission factor over the 6-year span of the *2019 Refinement* analysis was found to be relatively low).

Uncertainty regarding the identity of 3M emitted compounds

For the three 3M facilities that submitted their 1990 through 2010 emissions by fluorinated GHG group, it is assumed that the emissions of each group consist of the compounds in that group that were reported by species by the facility from 2011 through 2014. However, 3M indicated that the mix of products made at its facilities had changed over time, which would have affected the identities of the fluorinated GHGs emitted. For example, at one facility, only one compound was reported to be emitted for 2011-2015 but 3M's historical emissions data showed multiple fluorinated GHG groups for that facility for 1990 to 2010. For that facility, it is assumed that emissions consisted of the compounds in each gas type that were reported by species by the 3M facility that was determined to be the most similar. Additionally, there were a few years of data for these three facilities where some emissions were reported as a total rather than separated by group. For these years, the group shares were assumed to be

[67] For example, the DRE range 0 to 75% implies emissions of (1-0) x uncontrolled emissions to (1-75%) x uncontrolled emissions, or, rearranging and calculating, 0.25 x uncontrolled emissions to 1 x uncontrolled emissions, a factor of four.

the same as in nearby years. There is uncertainty involved with each of the assumptions made while speciating emissions for these three facilities, though the uncertainty is minimal regarding total emissions in metric tons of CO_2 Eq. In at least one case, the speciation method appears to have resulted in an overestimate for an individual compound. In this analysis, 3M's emissions of C_4F_8O are estimated to have peaked at around 410 MT in 2000, but at least one study has inferred considerably lower global emissions (around 120 MT) for that year based on atmospheric measurements of C_4F_8O (Vollmer et al. 2019).

2011-2022 Uncertainty

Emissions from 2011 to 2022 reflect reporting by fluorinated gas production facilities under the GHGRP. As discussed above, emissions reported under the GHGRP are based on facility- and process-specific measurements or calculations and are therefore expected to be reasonably accurate for the reporting facilities. (Emissions from the largest sources, process vents emitting 10,000 MT CO_2 Eq. or more annually, are estimated using Tier 3 methods.)

Unverified reports

Ninety-five percent (171/180) of the Subpart L reports submitted by fluorinated gas production facilities from 2011 to 2022 are considered to be fully verified; five percent (9/180) of the reports include one or more data elements that are not verified. One facility accounts for two thirds (6/9) of the unverified reports. Many of the issues in the unverified reports for this facility relate to time-series inconsistencies that have arisen as the facility updates reports for recent years, but not previous years, to reflect refinements to estimated emission rates. This facility has accounted for between 6 percent (in 2011) and 29 percent (in 2022) of the GWP-weighted emissions reported for this source category. The uncertainties for this facility therefore have an appreciable impact on the uncertainty of the estimates for the source category as a whole, particularly in years before 2022.

Facilities that do not produce fluorinated gases but may emit fluorinated GHGs from other fluorochemical production processes

Under the GHGRP, EPA collects information from facilities that produce fluorinated gases. While this likely includes most, and possibly all, U.S. facilities that produce fluorochemicals of any kind, it is possible that some fluorochemical producers do not report either their production of fluorochemicals or their emissions of fluorinated GHGs to EPA under the GHGRP. In this case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

At fluorinated gas production facilities that currently report their emissions under the GHGRP, it is possible that some processes that emit fluorinated GHGs neither produce nor transform a fluorinated gas, in which case their emissions would not be reported under the GHGRP. In that case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

Exclusion of nitrous oxide

The GHGRP does not currently require facilities to report emissions of nitrous oxide (N_2O) from fluorinated gas production or transformation, but the IPCC *2019 Refinement* includes a default emission factor for N_2O from production of NF_3, implying such emissions may occur. The GHGRP data (and this analysis) may therefore underestimate emissions of N_2O from fluorinated gas production. Because the GWP of N_2O is considerably lower than that of saturated HFCs, PFCs, and other fluorinated GHGs, any underestimate is expected to be relatively small.

Identity of emitted compounds

In this analysis, it is assumed that emissions that are reported only in MT CO_2 Eq. by fluorinated GHG group consist of the compounds in that group that are reported by species by the facility. However, if that were actually the case, emissions of those compounds would have been included in the speciated emissions rather than reported separately in MT CO_2 Eq. This analysis therefore incorrectly speciates some emissions. As noted in the Methodology section, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group is small, ranging

between 1 and 2 percent. Moreover, while the emissions are not assigned to the exact species emitted, they are assigned to a species that is closely related and likely to have similar atmospheric impacts (e.g., another saturated HFC with two or fewer carbon-hydrogen bonds). The impact of this uncertainty is therefore limited.

Quantities of Reactants Consumed or Fluorinated Gases Produced

The emissions reported under Subpart L are required to be calculated using process activity data, such as the quantity of reactants consumed or the quantity of the fluorinated gas product produced. In general, the uncertainties in process activity levels are expected to be small. The *2019 Refinement* places such uncertainties "in the region of 1 percent."

Because the uncertainties enumerated above are either small or difficult to quantify, EPA did not attempt to include them in the 2022 quantitative uncertainty estimate for this source category. The 2022 quantitative uncertainty estimate includes the following uncertainties:

Process Vent Emission Factors

Process vent emission factors that were developed based on stack testing (for continuous process vents emitting 10,000 MT CO_2 Eq. or more) were estimated to have an uncertainty (95-percent confidence interval) of ±35 percent based on Subpart L requirements.[68] Process vent emission factors that were developed based on calculations (for batch process vents and for continuous process vents emitting less than 10,000 MT CO_2 Eq.) were estimated to have a larger uncertainty of ±50 percent. Continuous processes were assumed to have two vents per process; batch processes were assumed to have five vents per process.[69]

Equipment Leak Estimates

The estimated equipment leaks reported by each facility for each process were estimated to have an uncertainty of ± 90 percent. The uncertainty of leak estimates depends on the method used to estimate leaks; there are multiple methods. For simplicity, this analysis uses a conservatively high uncertainty estimate that is appropriate for the Average EF Approach.

Venting of Residual Gas in Containers

The reported emissions of fluorinated GHGs from venting of residual gas in returned containers were estimated to have an uncertainty of ± 30 percent for each facility. This estimate is based on the Subpart L requirement to either measure the contents of each container or to measure the contents of at least 30 representative containers for each compound and container size and type.

Facilities that produce fluorinated gases but do not report their emissions to the GHGRP

EPA estimated emissions for fluorinated gas production facilities that do not report their emissions under Subpart L of the GHGRP. The estimates presented here for 2011 to 2022 are based on aggregated production estimates, the Tier 1 default emission factor in the *2019 Refinement*, and the default fluorinated GHG speciation from Table 3.28b (chapter 3.10.2 of *2019 Refinement*). There is considerable uncertainty in both the magnitude of the emissions and the identity of the emitted compounds. The *2019 Refinement* estimates the uncertainty of the Tier 1 emission factor as -98 percent to +470 percent. (In the quantitative uncertainty estimate below, which is based on error propagation, values of ±98 percent were used because error propagation requires the assumption of symmetric uncertainty bounds.) In 2022, estimated emissions from the six non-reporting facilities accounted for 44 percent of total estimated U.S. emissions from fluorinated gas production and transformation. In contrast,

---

[68] *Technical Support Document for Emissions from Production of Fluorinated Gases*, Office of Air and Radiation, U.S. Environmental Protection Agency, November 5, 2010. Available online at: https://www.epa.gov/sites/default/files/2015-02/documents/subpart-l_techsuppdoc.pdf.

[69] *Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions F-Gases: Subparts I, L, DD, QQ, SS*, U.S. Environmental Protection Agency, November 2010. Available online at: https://www.regulations.gov/document/EPA-HQ-OAR-2009-0927-0179.

production and transformation by these facilities accounted for just three percent of total fluorinated GHG production and transformation across all facilities. Because the emissions estimated for several of the six facilities exceeded the 25,000 MT CO_2 Eq. reporting threshold under Subpart L, but these facilities have not reported their emissions under Subpart L, it appears likely that emissions from at least some facilities are overestimated.

The four uncertainties listed immediately above were convolved using error propagation to arrive at an overall uncertainty estimate for 2022. The results of the Approach 1 quantitative uncertainty analysis are summarized in Table 4-72. Emissions of HFCs, PFCs, SF_6, and NF_3 from production of fluorochemicals other than HCFC-22 were estimated to fall between 4.83 and 7.08 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 5.95 MMT CO_2 Eq.

Table 4-72: Approach 1 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, and NF_3 from Production of Fluorochemicals other than HCFC-22 (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound[a]	Upper Bound[a]	Lower Bound	Upper Bound
Production of Fluorochemicals other than HCFC-22	HFCs, PFCs, SF_6, and NF_3	5.95	4.83	7.08	-19%	+19%

[a] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[70] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the Fluorinated Gas Production category. Under the GHGRP, fluorinated gas producers are required to (1) develop and periodically update process vent-specific emission factors using either measurements or engineering calculations, depending on the nature of the process (continuous vs. batch) and the magnitude of emissions from the vent, (2) take more measurements of vent emissions where variability is high, (3) use methods for sampling, measuring volumetric flow rates, non-fluorinated-GHG gas analysis, and measuring stack gas moisture that have been validated using a scientifically sound validation protocol, (4) use a quality-assured analytical measurement technology capable of detecting the analyte of interest at the concentration of interest and use a sampling and analytical procedure validated with the analyte of interest at the concentration of interest, (5) periodically test the performance of destruction devices used to control emissions, (6) account for any malfunctions in the process or destruction device, (6) account for emissions from equipment leaks, (7) measure the quantities of residual gas that are vented from returned containers (or develop an emission factor based on at least 30 measurements per gas and container size and type), (8) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable

[70] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

standards and suitable methods published by a consensus standards organization, (9) calibrate analytical equipment used to determine the concentration of fluorinated GHGs, and (10) document all measurements and calibrations.

The 1990, 1995, 2000, and 2002 through 2010 emissions data reported by 3M for three facilities was compared to the 1990 through 2010 emissions previously calculated for those facilities using the same calculation method used for other facilities that have reported their emissions under the GHGRP since 2011. The overall trajectory of the 3M-reported emissions, as well as the minima and maxima of those emissions, were similar to those previously calculated, but the increases and decreases in the 3M-reported emissions were more gradual. 3M explained that the gradual changes were due to changes in the compounds and quantities produced and to the gradual deployment and optimization of the destruction device at the 3M Cordova facility.

Recalculations

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

Planned Improvements

EPA is planning to refine its estimates of emissions from non-reporting facilities after confirming with the facilities that their actual per-facility uncontrolled emissions fall below 25,000 MT CO_2 Eq.. EPA is also planning to refine its estimates of emissions for other facilities between 1990 and 2009, e.g., by comparing these against emissions inferred from atmospheric measurements. Moreover, EPA is continuing to seek datasets that can be used to improve and/or QA/QC emissions estimates, particularly for the years 1990 to 2009. These datasets may include, for example, real-time facility-specific estimates or additional global "top-down," atmosphere-based emissions estimates that could be used to establish an upper limit on emissions of certain compounds.

4.16 Carbon Dioxide Consumption (CRT Source Category 2B10)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected underground to enable additional petroleum to be produced. For the purposes of this analysis, CO_2 used in food and beverage applications is assumed to be emitted to the atmosphere. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from CO_2 consumption. A further discussion of CO_2 used in EOR is described in the Energy chapter in Box 3-6 titled "Carbon Dioxide Transport, Injection, and Geological Storage" and is not included in this section.

Carbon dioxide is produced from naturally-occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component.

In 2022, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 5.0 MMT CO_2 Eq. (5,000 kt) (see Table 4-73 and Table 4-74). This is less than a 1 percent increase (10 kt) from 2021 levels and is an increase of approximately 240 percent (3,528 kt) since 1990.

Table 4-73: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0

Table 4-74: CO_2 Emissions from CO_2 Consumption (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000

Methodology and Time-Series Consistency

Carbon dioxide emission estimates for 1990 through 2022 utilize a country-specific method and were based on the quantity of CO_2 extracted and transferred for industrial applications (i.e., non-EOR end-uses). Some of the CO_2 produced by these facilities is used for EOR, and some is used in other commercial applications (e.g., chemical manufacturing, food and beverage). The IPCC does not have specific methodological guidelines for CO_2 consumption, but the country-specific methodology used is consistent with a Tier 3 approach since it relies on facility-specific information.

2010 through 2022

For 2010 through 2022, data from EPA's GHGRP (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the *Inventory* (EPA 2023). Facilities report CO_2 extracted or produced from natural reservoirs and industrial sites, and CO_2 captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO_2 transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO_2 transferred to other end-uses to enhance the completeness of estimates under this source category. Other end-uses include industrial applications, such as metal fabrication. EPA is analyzing the information reported to ensure that other end-use data excludes non-emissive applications and publication will not reveal CBI. Additionally, a small amount of CO_2 is used as a refrigerant; use and emissions from this application are reported under Section 4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F). Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO_2 that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality reasons and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO_2 extracted or produced. More details on the calculation and monitoring methods applicable to extraction and production facilities can be found under Subpart PP: Suppliers of Carbon Dioxide of the regulation, Part 98[71] The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2022 is much higher (ranging from 44 to 53) than the number of facilities included in the *Inventory* for the 1990 to 2009 time period prior to the availability of GHGRP data (4 facilities). The difference is largely due to the fact the 1990 to 2009 data includes only CO_2 transferred to end-use applications from naturally occurring CO_2 reservoirs and excludes industrial sites.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO_2 production data from four naturally-occurring CO_2 reservoirs were used to estimate annual CO_2 emissions. These facilities were Jackson Dome in Mississippi, Bravo and West Bravo Domes in New Mexico, and McCallum Dome in Colorado. The facilities in Mississippi and New Mexico produced CO_2 for use in both EOR and in other commercial applications (e.g.,

[71] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome) produced CO_2 for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006).

Carbon dioxide production data and the percentage of production that was used for non-EOR applications for the Jackson Dome, Mississippi facility were obtained from Advanced Resources International (ARI 2006, 2007) for 1990 to 2000, and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for 2001 to 2009 (see Table 4-75). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2009 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 1999 was set equal to 2000 production, due to lack of publicly available production data for 1990 through 1999. Carbon dioxide production data for the Bravo Dome and West Bravo Dome were obtained from ARI for 1990 through 2009 (ARI 1990 to 2010). Data for the West Bravo Dome facility were only available for 2009. The percentage of total production that was used for non-EOR applications for the Bravo Dome and West Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003; New Mexico Bureau of Geology and Mineral Resources 2006). Production data for the McCallum Dome (Jackson County), Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2009 (COGCC 2014). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999, due to lack of publicly available data.

Table 4-75: CO_2 Production (kt CO_2) and the Percent Used for Non-EOR Applications

Year	Jackson Dome, MS CO_2 Production (kt) (% Non-EOR)	Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	West Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	McCallum Dome, CO CO_2 Production (kt) (% Non-EOR)	Total CO_2 Production from Extraction and Capture Facilities (kt)	% Non-EOR[a]
1990	1,344 (100%)	63 (1%)	+	65 (100%)	NE	NE
2005	1,254 (27%)	58 (1%)	+	63 (100%)	NE	NE
2018	IE	IE	IE	IE	58,400[b]	7%
2019	IE	IE	IE	IE	61,300[b]	8%
2020	IE	IE	IE	IE	44,700[b]	11%
2021	IE	IE	IE	IE	43,980[b]	11%
2022	IE	IE	IE	IE	46,800[b]	11%

+ Does not exceed 0.5 percent.
NE (Not Estimated)
IE (Included Elsewhere)
[a] Includes only food and beverage applications.
[b] For 2010 through 2022, the publicly available GHGRP data were aggregated at the national level based on GHGRP CBI criteria. The Dome-specific CO_2 production values are accounted for (i.e., included elsewhere) in the Total CO_2 Production from Extraction and Capture Facilities values starting in 2010 and are not able to be disaggregated.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for CO_2 consumption spliced activity data from two different sources: Industry data for 1990 through 2009 and GHGRP data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap (IPCC 2006). The data sets were determined to be inconsistent; the GHGRP data include CO_2 from industrial sources while the industry data do not. No adjustments were made to the activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent.

Uncertainty

There is uncertainty associated with the data reported through EPA's GHGRP. Specifically, there is uncertainty associated with the amount of CO_2 consumed for food and beverage applications, given the GHGRP does have provisions that Subpart PP reporters are not required to report to the GHGRP if their emissions fall below certain

thresholds, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. Second, uncertainty is associated with the exclusion of imports/exports data for CO_2 suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[72] Given the lack of specific uncertainty ranges available on the data used, EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 consumed for food and beverage applications. The uncertainty range is derived from the default range for solvent use in Section 5.5 of Chapter 3 of the *2006 IPCC Guidelines*. These values are representative of CO_2 used in food and beverage based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-76. Carbon dioxide consumption CO_2 emissions for 2022 were estimated to be between 4.8 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 5.0 MMT CO_2 Eq.

Table 4-76: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2 Consumption	CO_2	5.0	4.8	5.2	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to CO_2 Consumption can be found under Subpart PP (Suppliers of Carbon Dioxide) of the regulation (40 CFR Part 98).[73] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[74] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

[72] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[73] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[74] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve the accuracy and completeness of estimates for this source category. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[75]

These improvements are still in process and will be incorporated into future *Inventory* reports. These are near-to medium-term improvements.

4.17 Phosphoric Acid Production (CRT Source Category 2B10)

Phosphoric acid (H_3PO_4) is a basic raw material used in the production of phosphate-based fertilizers. Phosphoric acid production from natural phosphate rock is a source of carbon dioxide (CO_2) emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock. This reporting category (2B10) includes emissions that do not fall within any other CRT source category, which includes production of phosphoric acid. Emissions from fuels consumed for energy purposes during the production of phosphoric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Phosphate rock is mined in Florida and North Carolina, which account for more than 75 percent of total domestic output, and in Idaho and Utah (USGS 2023). It is used primarily as a raw material for wet-process phosphoric acid production. The composition of natural phosphate rock varies, depending on the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic carbon in the form of calcium carbonate (limestone) and may also contain organic carbon.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). Phosphate rock also contains naturally occurring limestone ($CaCO_3$), ranging from 0.2 to 4.5 percent (as CO_2), with domestic phosphate rock from Florida containing 3.1 percent limestone (as CO_2) (EFMA 2000). The generation of CO_2 from limestone in the phosphate rock is from the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

Total U.S. phosphate rock production in 2022 was an estimated 21 million metric tons (USGS 2023). Between 1990 and 2022, domestic phosphate rock production decreased by approximately 58 percent. Total imports of phosphate rock to the United States in 2022 were 2.4 million metric tons (USGS 2023). Between 2018 and 2021, most of the imported phosphate rock (95 percent) came from Peru, with 5 percent from Morocco (USGS 2023). All phosphate rock mining companies in the United States are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines.

Total CO_2 emissions from phosphoric acid production were 0.8 MMT CO_2 Eq. (840 kt CO_2) in 2022 (see Table 4-77 and Table 4-78). Domestic consumption of phosphate rock in 2022 was estimated to have decreased 3.9 percent

[75] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

relative to 2021 levels. The COVID-19 pandemic did not impact the domestic phosphate rock market as both the fertilizer industry and related agricultural businesses were considered essential industries and were unaffected by pandemic "stay-at-home" orders issued in March 2020 (USGS 2021a).

Table 4-77: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8

Table 4-78: CO_2 Emissions from Phosphoric Acid Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840

Methodology and Time-Series Consistency

The United States uses a country-specific methodology consistent with and comparable to an IPCC Tier 1 approach to calculate emissions from production of phosphoric acid from phosphate rock based on the stoichiometry of the process reaction shown above. The *2006 IPCC Guidelines* do not provide a method for estimating process emissions (CO_2) from phosphoric acid production. Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO_2) contained in the natural phosphate rock as calcium carbonate by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption. The estimation methodology is as follows:

Equation 4-10: CO_2 Emissions from Phosphoric Acid Production

$$E_{pa} = C_{pr} \times Q_{pr}$$

where,

E_{pa} = CO_2 emissions from phosphoric acid production, metric tons

C_{pr} = Average amount of carbon (expressed as CO_2) in natural phosphate rock, metric ton CO_2/ metric ton phosphate rock

Q_{pr} = Quantity of phosphate rock used to produce phosphoric acid

The CO_2 emissions calculation methodology assumes that all of the inorganic carbon (calcium carbonate) content of the phosphate rock reacts to produce CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic carbon content of the phosphate rock is converted to CO_2 and that all of the organic carbon content remains in the phosphoric acid product.

From 1993 to 2004, the U.S. Geological Survey (USGS) *Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-79). For the years 1990 through 1992, and 2005 through 2022, only nationally aggregated mining data was reported by USGS. For the years 1990, 1991, and 1992, the breakdown of phosphate rock mined in Florida and North Carolina and the amount mined in Idaho and Utah are approximated using data reported by USGS for the average share of U.S. production in those states from 1993 to 2004. For the years 2005 through 2022, the same approximation method is used, but the share of U.S. production was assumed to be consistent with the ratio of production capacity in those states, which were obtained from the USGS commodity specialist for phosphate rock (USGS 2012; USGS 2021b). For 1990 through 2022, data on U.S. domestic consumption of phosphate rock, consisting of domestic reported sales and use of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption, were obtained from USGS *Minerals Yearbook: Phosphate Rock*

(USGS 1994 through 2015b) and from USGS *Minerals Commodity Summaries: Phosphate Rock* (USGS 2016 through 2021a, 2022). From 2004 through 2022, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2022).

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research, now known as the Florida Industrial and Phosphate Research Institute (FIPR 2003a). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-79). Similar to the phosphate rock mined in Morocco, phosphate rock mined in Peru contains approximately 5 percent CO_2 (Golder Associates and M3 Engineering 2016).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (more than 75 percent of domestic production), and carbonate content data for phosphate rock mined in Morocco and Peru are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation assumes that all of the domestic production of phosphate rock is used in uncalcined form. As of 2006, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). The USGS confirmed that no significant quantity of domestic production of phosphate rock is in the calcined form (USGS 2012).

Table 4-79: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990	2005	2018	2019	2020	2021	2022
U.S. Domestic Consumption[a]	49,800	35,200	23,300	23,400	22,600	21,900	21,000
FL and NC	*42,494*	*28,160*	*18,170*	*18,250*	*17,630*	*17,080*	*16,380*
ID and UT	*7,306*	*7,040*	*5,130*	*5,150*	*4,970*	*4,820*	*4,620*
Exports—FL and NC	6,240	0	0	0	0	0	0
Imports	451	2,630	2,770	2,140	2,520	2,460	2,400
Total U.S. Consumption	**44,011**	**37,830**	**26,070**	**25,540**	**25,120**	**24,360**	**23,400**

[a] U.S. domestic consumption values are based on reported phosphate rock sold or used by producers.
Note: Totals may not sum due to independent rounding.

Table 4-80: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco	Peru
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56	NA
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46	NA
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10	NA
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00	5.00

NA (Not Available)
Sources: FIPR (2003a), Golder Associates and M3 Engineering (2016)

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2021. Prior to 2006, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was

reported. Regional production for 2021 was estimated based on regional production data from 2017 to 2020 and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2021 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for exports of phosphate rock used in the emission calculations are reported to the USGS by phosphate rock producers and are not considered to be a significant source of uncertainty. Data for imports for consumption are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty. Based on expert judgement of the USGS, EPA assigned an uncertainty range of ±5 percent to the percentage of phosphate rock produced from Florida and North Carolina, and ±5 percent to phosphoric acid production and imports (USGS 2012). Per this expert judgment, a normal probability density function was assigned for all activity data.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock, as the composition of phosphate rock varies depending upon where the material is mined and may also vary over time. The *Inventory* relies on one study (FIPR 2003a) of chemical composition of the phosphate rock; limited data are available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of FIPR indicated that in the phosphoric acid production process, the organic carbon content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003b). Organic carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic carbon in the phosphate rock into CO_2; however, according to air permit information available to the public, at least one facility has calcining units permitted for operation (NCDENR 2013).

Finally, USGS indicated that in 2021 less than 5 percent of domestically-produced phosphate rock was used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2022). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions assumes that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic carbon content in phosphate rock, but none from the organic carbon content.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-81. 2022 phosphoric acid production CO_2 emissions were estimated to be between 0.7 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.8 MMT CO_2 Eq.

Table 4-81: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	0.8	0.7	1.1	-18%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2021 to reflect updated USGS data on the total U.S. production of phosphate rock. This update resulted in a decrease of 35 kt CO_2 in 2021.

Planned Improvements

EPA continues to evaluate potential improvements to the *Inventory* estimates for this source category, which include direct integration of EPA's GHGRP data for 2010 through 2022 along with assessing applicability of reported GHGRP data to update the inorganic carbon content of phosphate rock for prior years to ensure time-series consistency. Specifically, EPA would need to assess that averaged inorganic carbon content data (by region or other approaches) meets GHGRP confidential business information (CBI) screening criteria. EPA would then need to assess the applicability of GHGRP data for the averaged inorganic carbon content (by region or other approaches) from 2010 through 2022, along with other information to inform estimates in prior years in the time series (1990 through 2009) based on the sources of phosphate rock used in production of phosphoric acid over time. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely upon the latest guidance from the IPCC on the use of facility-level data in national inventories.[76] These long-term planned improvements are still in development by EPA and have not been implemented into the current *Inventory* report.

4.18 Iron and Steel Production (CRT Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO_2) and methane (CH_4) as raw materials are refined into iron and then transformed into crude steel. This reporting category (2C1) includes emissions from the production of iron and steel. Per the IPCC methodological guidance, emissions from conventional fuels (e.g., natural gas, fuel oil) consumed for energy purposes during the production of iron and steel are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Iron and steel production includes seven distinct production processes: metallurgical coke production, sinter production, direct reduced iron (DRI) production, pellet production, pig iron.[77] production, electric arc furnace

[76] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

[77] Pig iron is the common industry term to describe what should technically be called crude iron. Pig iron is a subset of crude iron that has lost popularity over time as industry trends have shifted. Throughout this report, pig iron will be used

(EAF) steel production, and basic oxygen furnace (BOF) steel production. The number of production processes at a particular plant is dependent upon the specific plant configuration. Most process CO_2 generated from the iron and steel industry is a result of the production of crude iron.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold off-site for use as synthetic natural gas are also accounted for in these calculations. In general, CO_2 emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). Fugitive CH_4 emissions can also be generated from these processes, as well as from sinter, direct iron, and pellet production.

In 2022, approximately eleven integrated iron and steel steelmaking facilities utilized BOFs to refine and produce steel from iron, and raw steel was produced at 101 facilities across the United States. As of 2020, approximately 29 percent of steel production was attributed to BOFs and 71 percent to EAFs (AISI 2020). The trend in the United States for integrated facilities has been a shift towards fewer BOFs and more EAFs. EAFs use scrap steel as their main input and use significantly less energy than BOFs. There are also 14 cokemaking facilities, of which 3 facilities are co-located with integrated iron and steel facilities (ACCCI 2021). In the United States, seven states account for roughly 61 percent of total raw steel production: Indiana, Alabama, Tennessee, Kentucky, Mississippi, Arkansas, and Ohio (AISI 2023).

Total annual production of crude steel in the United States was fairly constant between 2000 and 2008 and ranged from a low of 99,320,000 tons to a high of 109,880,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn (particularly from the automotive industry), crude steel production in the United States sharply decreased to 65,459,000 tons in 2009. Crude steel production was fairly constant from 2011 through 2014, and after a dip in production from 2014 to 2015, crude steel production steadily increased. Crude steel production dipped again in 2020 due to the COVID-19 pandemic and returned to pre-pandemic levels in 2021. Production declined by approximately 6 percent in 2022 (AISI 2023). This decline may be attributable to projections for decreased global end-use consumption due to multiple factors including the conflict in Ukraine, continuing coronavirus disease 2019 (COVID-19) mitigation measures in China, rising energy costs and interest rates, and global inflation (USGS 2023a). The United States was the fourth largest producer of raw steel in the world, behind China, India, and Japan, accounting for approximately 4.3 percent of world production in 2022 (AISI 2004 through 2023).

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of carbon-containing flux and from the removal of carbon from pig iron used to produce steel.

According to the *2006 IPCC Guidelines*, the production of metallurgical coke from coking coal is considered to be an energy use of fossil fuel, and the use of coke in iron and steel production is considered to be an industrial process source. The *2006 IPCC Guidelines* suggest that emissions from the production of metallurgical coke should be reported separately in the Energy sector, while emissions from coke consumption in iron and steel production should be reported in the Industrial Processes and Product Use sector. The approaches and emission estimates for both metallurgical coke production and iron and steel production, however, are presented here because much of the relevant activity data is used to estimate emissions from both metallurgical coke production and iron and steel production. For example, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed at the point of consumption. Emissions associated with the use of conventional

interchangeably with crude iron, but it should be noted that in other data sets or reports pig iron and crude iron may not be used interchangeably and may provide different values.

fuels (e.g., natural gas, fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 from metallurgical coke production in 2022 were 3.0 MMT CO_2 Eq. (2,954 kt CO_2) (see Table 4-82 and Table 4-83). Emissions decreased by 8 percent from 2021 to 2022 and have decreased by 47 percent since 1990. Coke production in 2022 was about 9 percent lower than in 2021 and 59 percent below 1990 (EIA 2023, AISI 2023).

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

Table 4-82: CO_2 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5.6	3.9	1.3	3.0	2.3	3.2	3.0

Table 4-83: CO_2 Emissions from Metallurgical Coke Production (kt CO_2)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5,608	3,921	1,282	3,006	2,325	3,224	2,954

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2022 were 37.7 MMT CO_2 Eq. (37,718 kt) and 0.0077 MMT CO_2 Eq. (0.3 kt CH_4), respectively (see Table 4-84 through Table 4-87). Emissions from iron and steel production decreased by 2 percent from 2021 to 2022 and have decreased by 62 percent since 1990, due to restructuring of the industry, technological improvements, and increased scrap steel utilization. Carbon dioxide emission estimates include emissions from the consumption of carbonaceous materials in the blast furnace, EAF, and BOF, as well as blast furnace gas and coke oven gas consumption for other activities at the steel mill.

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

In 2022, domestic production of pig iron decreased by 11 percent from 2021 levels. Overall, domestic pig iron production has declined since the 1990s; pig iron production in 2022 was 59 percent lower than in 2000 and 60 percent below 1990. Carbon dioxide emissions from iron production have decreased by 81 percent (37.0 MMT CO_2 Eq.) since 1990. Carbon dioxide emissions from steel production have decreased by 16 percent (1.3 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 62 percent (61.4 MMT CO_2 Eq.) from 1990 to 2022.

Table 4-84: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2.4	1.7	0.9	0.9	0.7	0.8	0.8
Iron Production	45.7	17.7	9.6	9.4	8.4	9.0	8.7
Pellet Production	1.8	1.5	0.9	0.9	0.8	0.8	0.8
Steel Production	8.0	9.4	6.0	5.8	5.7	5.8	6.7
Other Activities[a]	41.2	35.9	24.1	23.2	19.8	22.1	20.8
Total	**99.1**	**66.2**	**41.6**	**40.1**	**35.4**	**38.6**	**37.7**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.
Note: Totals may not sum due to independent rounding.

Table 4-85: CO_2 Emissions from Iron and Steel Production (kt CO_2)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2,448	1,663	937	876	749	836	787
Iron Production	45,709	17,666	9,589	9,365	8,420	9,038	8,673
Pellet Production	1,817	1,503	924	878	751	838	789
Steel Production	7,964	9,395	5,982	5,812	5,657	5,816	6,655
Other Activities [a]	41,194	35,934	24,149	23,158	19,820	22,119	20,814
Total	**99,132**	**66,161**	**41,581**	**40,089**	**35,398**	**38,648**	**37,718**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.
Note: Totals may not sum due to independent rounding.

Table 4-86: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	+	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-87: CH_4 Emissions from Iron and Steel Production (kt CH_4)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	0.9	0.6	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emission estimates for metallurgical coke, EAF steel production, and BOF steel production presented in this chapter utilize a country-specific approach based on Tier 2 methodologies provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Estimates for pig iron production apply Tier 2 methods consistent with the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and DRI production) for which available data are insufficient to apply a Tier 2 method (e.g., country-specific carbon contents of inputs and outputs are not known). The majority of emissions are captured with higher tier methods, as sinter production, pellet production, and DRI production only account for roughly 8 percent of total iron and steel production emissions.

The Tier 2 methodology equation is as follows:

Equation 4-11: CO_2 Emissions from Coke, Pig Iron, EAF Steel, and BOF Steel Production, based on *2006 IPCC Guidelines* Tier 2 Methodologies

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b)\right] \times \frac{44}{12}$$

where,

E_{CO2} = Emissions from coke, pig iron, EAF steel, or BOF steel production, metric tons

a = Input material *a*

b = Output material *b*

Q_a = Quantity of input material *a*, metric tons

C_a = Carbon content of input material *a*, metric tons C/metric ton material

Q_b = Quantity of output material *b*, metric tons

C_b = Carbon content of output material *b*, metric tons C/metric ton material

44/12 = Stoichiometric ratio of CO_2 to C

The Tier 1 methodology equations are as follows:

Equation 4-12: *2006 IPCC Guidelines* Tier 1: Emissions from Sinter, Direct Reduced Iron, and Pellet Production (Equations 4.6, 4.7, and 4.8)

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO2} = Q_d \times EF_{d,CO2}$$

$$E_{p,CO2} = Q_p \times EF_{p,CO2}$$

where,

$E_{s,p}$ = Emissions from sinter production process for pollutant *p* (CO_2 or CH_4), metric ton

Q_s = Quantity of sinter produced, metric tons

$EF_{s,p}$ = Emission factor for pollutant *p* (CO_2 or CH_4), metric ton *p*/metric ton sinter

$E_{d,CO2}$ = Emissions from DRI production process for CO_2, metric ton

Q_d = Quantity of DRI produced, metric tons

$EF_{d,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton DRI

$E_{p,CO2}$ = Emissions from pellet production process for CO_2, metric ton

Q_p = Quantity of pellets produced, metric tons

$EF_{p,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton pellets produced

A significant number of activity data that serve as inputs to emissions calculations were unavailable for 2020 through 2022 at the time of publication and were estimated using 2019 values. To estimate annual emissions for these years, the EPA used process emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) subpart Q for the iron and steel sector to adjust the estimated values for 2020 through 2022. GHGRP process emissions data decreased by approximately 14 percent from 2019 to 2020, increased by approximately 12 percent from 2020 to 2021, and decreased by approximately 6 percent from 2021 to 2022 (EPA 2023). These percentage changes were applied to 2019 activity data values to produce estimates for 2020 through 2022.

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke which is used primarily as a reducing agent in the production of iron and steel but is also used in the production of other metals including zinc and lead (see Zinc Production and Lead Production sections of this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated and reported separately from emissions that result from the iron and steel production process. To estimate emissions from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* was

utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze and coke oven gas) is deducted from the amount of carbon contained in materials consumed during the metallurgical coke production process (i.e., natural gas, blast furnace gas, and coking coal). For calculations, activity data for these inputs, including natural gas, blast furnace gas, and coking coke consumed for metallurgical coke production, are in units consistent with the carbon content values. Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-88). The amount of coal tar produced was approximated using a production factor of 0.03 tons of coal tar per ton of coking coal consumed. The amount of coke breeze produced was approximated using a production factor of 0.075 tons of coke breeze per ton of coking coal consumed (Steiner 2008; DOE 2000). Data on the consumption of carbonaceous materials (other than coking coal) as well as coke oven gas production were available for integrated steel mills only (i.e., steel mills with co-located coke plants); therefore, carbonaceous material (other than coking coal) consumption and coke oven gas production were excluded from emission estimates for merchant coke plants. Carbon contained in coke oven gas used for coke-oven underfiring was not included in the deductions to avoid double-counting.

Table 4-88: Material Carbon Contents for Metallurgical Coke Production

Material	kg C/kg
Coal Tar[a]	0.62
Coke[a]	0.83
Coke Breeze[a]	0.83
Coking Coal[b]	0.75
Material	**kg C/GJ**
Coke Oven Gas[c]	12.1
Blast Furnace Gas[c]	70.8

[a] Source: IPCC (2006), Vol. 3 Chapter 4, Table 4.3
[b] Source: EIA (2017b)
[c] Source: IPCC (2006), Vol. 2 Chapter 1, Table 1.3

Although the *2006 IPCC Guidelines* provide a Tier 1 CH_4 emission factor for metallurgical coke production (i.e., 0.1 g CH_4 per metric ton of coke production), it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the metallurgical coke production process either exits the process as part of a carbon-containing output or as CO_2 emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH_4 emissions reported by coke production facilities under EPA's GHGRP. The assessment indicates that CH_4 emissions from coke production are insignificant and below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA continues to assess the possibility of including these emissions in future Inventories to enhance completeness but has not incorporated these emissions into this report.

Data relating to the mass of coking coal consumed at metallurgical coke plants and the mass of metallurgical coke produced at coke plants were taken from the Energy Information Administration (EIA) *Quarterly Coal Report: October through December* (EIA 1998 through 2019) and EIA *Quarterly Coal Report: January through March* (EIA 2021 through 2023) (see Table 4-89). Data on the volume of natural gas consumption, blast furnace gas consumption, and coke oven gas production for metallurgical coke production at integrated steel mills were obtained from the American Iron and Steel Institute (AISI) *Annual Statistical* Report (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008) (see Table 4-90). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (Steiner 2008). The factor for the quantity of coke breeze produced per ton of coking coal consumed was obtained through Table 2-1 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). Data on

natural gas consumption and coke oven gas production at merchant coke plants were not available and were excluded from the emission estimate. Carbon contents for metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines*. The carbon content for coke breeze was assumed to equal the carbon content of coke. Carbon contents for coking coal was from EIA.

Table 4-89: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	16,635	16,261	13,076	15,957	14,523
Coke Production at Coke Plants	25,054	15,167	12,525	11,676	9,392	11,381	10,337
Coke Breeze Production	2,645	1,594	1,248	1,220	981	1,197	1,089
Coal Tar Production	1,058	638	499	488	392	479	436

Table 4-90: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	80,750	77,692	66,492	74,206	69,829
Natural Gas Consumption	599	2,996	2,275	2,189	1,873	2,091	1,967
Blast Furnace Gas Consumption	24,602	4,460	4,022	3,914	3,350	3,738	3,518

Iron and Steel Production

To estimate emissions from pig iron production in the blast furnace, the amount of carbon contained in the produced pig iron and blast furnace gas were deducted from the amount of carbon contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, carbonate fluxes or slagging materials, and direct coal injection). For calculations, activity data for these inputs, including coke consumed for pig iron production, are in units consistent with the carbon content values. The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific carbon content by each material type (see Table 4-91). In the absence of a default carbon content value from the *2006 IPCC Guidelines* for pellet, sinter, or natural ore consumed for pig iron production, a country-specific approach based on Tier 2 methodology is used. Pellet, sinter, and natural ore used as an input for pig iron production is assumed to have the same carbon content as direct reduced iron (2 percent), based on expert judgment (RTI 2024). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process. Carbon contained in blast furnace gas used as a blast furnace input was not included in the deductions to avoid double-counting.

Emissions from steel production in EAFs were estimated by deducting the carbon contained in the steel produced from the carbon contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of carbon from DRI and pig iron to the EAFs were also included in the EAF calculation. For BOFs, estimates of carbon contained in BOF steel were deducted from carbon contained in inputs such as natural gas, coke oven gas, fluxes (i.e., limestone and dolomite), and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-91). For EAFs, the amount of EAF anode consumed was approximated by multiplying total EAF steel production by the amount of EAF anode consumed per metric ton of steel produced (0.002 metric tons EAF anode per metric ton steel produced [Steiner 2008]). The amount of carbon-containing flux (i.e., limestone and dolomite) used in EAF and BOF steel production was deducted from the "Other Process Uses of Carbonates" source category (CRT Source Category 2A4) to avoid double-counting.

Carbon dioxide emissions from the consumption of blast furnace gas and coke oven gas for other activities occurring at the steel mill were estimated by multiplying the amount of these materials consumed for these purposes by the material-specific carbon content (see Table 4-91).

Table 4-91: Material Carbon Contents for Iron and Steel Production

Material	kg C/kg
Coke	0.83
Direct Reduced Iron	0.02
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Limestone	0.12
Pig Iron	0.04
Steel	0.01
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and Blast Furnace Gas, Table 1.3.

Carbon dioxide emissions associated with sinter production, direct reduced iron production, pellet production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-84 and Table 4-85).

The sinter production process results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment, rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines* for sinter production (see Table 4-92). Although the *2006 IPCC Guidelines* also provide a Tier 1 methodology for CH_4 emissions from pig iron production, it is not appropriate to use because CO_2 emissions for pig iron production are estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the pig iron production process either exits the process as part of a carbon-containing output or as CO_2 emissions; the estimation of CH_4 emissions is precluded. Annual analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH_4 emissions are below 500 kt CO_2 Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron could also result in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas, etc.); however, these emission estimates are excluded due to data limitations. Pending further analysis and resources, EPA may include these emissions in future reports to enhance completeness. EPA is still assessing the possibility of including these emissions in future reports and have not included this data in the current report.

Table 4-92: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Sinter	0.07	kg CH_4/metric ton

Source: IPCC (2006), Table 4.2.

Emissions of CO_2 from sinter production, direct reduced iron production, and pellet production were estimated by multiplying total national sinter production, total national direct reduced iron production, and total national pellet production by Tier 1 CO_2 emission factors (see Table 4-93). Because estimates of sinter production, direct reduced iron production, and pellet production were not available, production was assumed to equal consumption.

Table 4-93: CO_2 Emission Factors for Sinter Production, Direct Reduced Iron Production, and Pellet Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7
Pellet Production	0.03

Source: IPCC (2006), Table 4.1.

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted for within the Energy chapter to avoid double-counting of emissions reported within the IPPU chapter as these fuels were consumed during non-energy related activities. More information on this methodology and examples of adjustments made between the IPPU and Energy chapters are described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Sinter consumption and pellet consumption data for 1990 through 2020 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (Steiner 2008) (see Table 4-94). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

In general, direct reduced iron (DRI) consumption data were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data for DRI consumed in EAFs were not available for the years 1990 and 1991. EAF DRI consumption in 1990 and 1991 was calculated by multiplying the total DRI consumption for all furnaces by the EAF share of total DRI consumption in 1992. Data for DRI consumed in BOFs were not available for the years 1990 through 1993. BOF DRI consumption in 1990 through 1993 was calculated by multiplying the total DRI consumption for all furnaces (excluding EAFs and cupola) by the BOF share of total DRI consumption (excluding EAFs and cupola) in 1994.

The Tier 1 CO_2 emission factors for sinter production, direct reduced iron production and pellet production were obtained through the *2006 IPCC Guidelines* (IPCC 2006). Time-series data for pig iron production, coke, natural gas, fuel oil, sinter, and pellets consumed in the blast furnace; pig iron production; and blast furnace gas produced at the iron and steel mill and used in the metallurgical coke ovens and other steel mill activities were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008) (see Table 4-94 and Table 4-95). Data including blast furnace gas, coke oven gas, natural gas, limestone, sinter, and natural ore consumption for blast furnaces, coke production, and steelmaking furnaces (EAFs and BOFs) from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Similarly, the percent of total steel production for EAF and BOF steelmaking processes were withheld for 2021 and 2022, so the 2020 values were used as estimated data for the missing 2021 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data for EAF steel production, carbon-containing flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (AISI 2006 through 2016, Steiner 2008). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (Steiner 2008). Data for BOF steel production, carbon-containing flux, natural gas, natural ore, pellet, sinter consumption as well as BOF steel production were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008). Data for EAF consumption of natural gas and BOF consumption of coke oven gas, limestone, and natural ore from the AISI *Annual Statistical Report* were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this

Methodology and Time-Series Consistency section. Data for EAF and BOF scrap steel, pig iron, and DRI consumption were obtained from the USGS *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data on coke oven gas and blast furnace gas consumed at the iron and steel mill (other than in the EAF, BOF, or blast furnace) were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008). These data were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Some data from the *AISI Annual Statistical Report* on natural gas consumption were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's *Natural Gas Annual 2019* (EIA 2020). Carbon contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines*. The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (EIA 2017b) and EPA (EPA 2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (EIA 1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021) and confirmed by AISI staff (Carroll 2016).

Table 4-94: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	12,239	8,315	4,687	4,378	3,747	4,182	3,935
Direct Reduced Iron Production	517	1,303	C	C	C	C	C
Pellet Production	60,563	50,096	30,793	29,262	25,044	27,949	26,300
Pig Iron Production							
Coke Consumption	24,946	13,832	7,618	7,291	6,240	6,964	6,553
Pig Iron Production	49,669	37,222	24,058	22,302	18,320	22,246	19,791
Direct Injection Coal Consumption	1,485	2,573	2,569	2,465	2,110	2,354	2,216
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,133	1,137	1,118	1,129	1,123
Scrap Steel Consumption	42,691	46,600	C	C	C	C	C
Flux Consumption	319	695	998	998	998	998	998
EAF Steel Production	33,511	52,194	58,904	61,172	51,349	57,307	53,926
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	C	C	C	C	C
Scrap Steel Consumption	14,713	11,400	C	C	C	C	C
Flux Consumption	576	582	408	363	311	347	326
BOF Steel Production	43,973	42,705	27,704	26,591	21,384	23,865	22,457

C (Confidential)

Table 4-95: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (Million ft^3 unless otherwise specified)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	40,204	37,934	32,465	36,232	34,095
Fuel Oil Consumption (thousand gallons)	163,397	16,170	3,365	2,321	1,986	2,217	2,086

Coke Oven Gas Consumption	22,033	16,557	13,337	12,926	11,063	12,346	11,618
Blast Furnace Gas Production	1,439,380	1,299,980	871,860	836,033	715,509	798,522	751,418
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	8,556	9,115	7,801	8,706	8,192
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	405	389	333	372	350
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	67,008	64,377	55,096	61,489	57,861
Blast Furnace Gas Consumption	1,414,778	1,295,520	867,838	832,119	712,159	794,783	747,900

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The estimates of CO_2 emissions from metallurgical coke production are based on assessing uncertainties in material production and consumption data and average carbon contents. Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production, and materials consumed during this process. Data for coking coal consumption and metallurgical coke production are from different data sources (EIA) than data for other carbonaceous materials consumed at coke plants (AISI), which does not include data for merchant coke plants. There is uncertainty associated with the fact that coal tar and coke breeze production were estimated based on coke production because coal tar and coke breeze production data were not available. Since merchant coke plant data is not included in the estimate of other carbonaceous materials consumed at coke plants, the mass balance equation for CO_2 from metallurgical coke production cannot be reasonably completed; therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average carbon contents. There is uncertainty associated with the assumption that pellet production, direct reduced iron and sinter consumption are equal to production. There is uncertainty with the representativeness of the associated IPCC default emission factors. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal. There is also uncertainty associated with the carbon contents for pellets, sinter, and natural ore, which are assumed to equal the carbon contents of direct reduced iron, when consumed in the blast furnace. There is uncertainty associated with the consumption of natural ore under current industry practices. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge carbon consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to "steelmaking furnaces" by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas. Data are not available to differentiate between the use of these gases for processes at the steel mill versus for energy generation (i.e., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions; however, there are uncertainties associated with each.

For calculating the emissions estimates from iron and steel and metallurgical coke production, EPA utilizes a number of data points taken from the AISI *Annual Statistical Report* (ASR). This report serves as a benchmark for information on steel companies in United States, regardless if they are a member of AISI, which represents integrated producers (i.e., blast furnace and EAF). During the compilation of the 1990 through 2016 *Inventory* report EPA initiated conversation with AISI to better understand and update the qualitative and quantitative uncertainty metrics associated with AISI data elements. AISI estimates their data collection response rate to range from 75 to 90 percent, with certain sectors of the iron and steel industry not being covered by the ASR; therefore, there is some inherent uncertainty in the values provided in the AISI ASR, including material production and consumption data. There is also some uncertainty to which materials produced are exported to Canada. As

indicated in the introduction to this section, the trend for integrated facilities has moved to more use of EAFs and fewer BOFs. This trend may not be completely captured in the current data which also increases uncertainty. EPA assigned an uncertainty range of ±10 percent for the primary data inputs (i.e., consumption and production values for each production process, heat and carbon content values), a normal probability density function for consumption and production values for each production process, and a triangular probability density function for heat and carbon content values to calculate overall uncertainty from iron and steel production, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). During EPA's discussion with AISI, AISI noted that an uncertainty range of ±5 percent would be a more appropriate approximation to reflect their coverage of integrated steel producers in the United States. EPA will continue to assess the best range of uncertainty for these values. EPA assigned an uncertainty range of ±25 percent and a triangular probability density function for the Tier 1 CO_2 emission factors for the sinter, direct reduced iron, and pellet production processes, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-96 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 34.3 and 47.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 16 percent above the emission estimate of 40.7 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 0.007 and 0.008 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 0.0077 MMT CO_2 Eq.

Table 4-96: Approach 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Metallurgical Coke & Iron and Steel Production	CO_2	40.7	34.3	47.1	-16%	+16%
Metallurgical Coke & Iron and Steel Production	CH_4	+	+	+	-7%	+7%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). As part of a multiyear improvement effort, EPA is reviewing the iron and steel methodology and available data, conducting additional category specific QC checks and will report on findings when that review is complete (i.e., projected to be complete at earliest for the 2025 report). More information is provided under Planned Improvements below.

Recalculations Discussion

Recalculations were performed for the year 2021 with updated USGS values for DRI, pig iron, and scrap steel consumption for both BOF and EAF steel production. Additionally, revisions to GHGRP data for 2020 and 2021 resulted in minor changes to activity data that were adjusted using GHGRP data, as described in the Methodology and Time-Series Consistency section. Compared to the previous *Inventory*, CO_2 emissions from steel production increased by less than 1 percent (7 kt CO_2) in 2020 and by less than 1 percent (211 kt CO_2) in 2021.

Planned Improvements

Significant activity data for 2020 through 2022 were not available for this report and were estimated using 2019 values and adjusted using GHGRP emissions data. EPA will continue to explore sources of 2020 through 2022 data and other estimation approaches. EPA will evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for Iron and Steel Production process categories. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[78] This is a near to medium-term improvement, and per preliminary work, EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

Additional improvements include accounting for emission estimates for the production of metallurgical coke in the Energy chapter as well as identifying the amount of carbonaceous materials, other than coking coal, consumed at merchant coke plants. Other potential improvements include identifying the amount of coal used for direct injection and the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters. Additional efforts will be made to improve the reporting and transparency in accounting for fuels between the IPPU and Energy chapters, particularly the inclusion of a quantitative summary of the carbon balance in the United States. This planned improvement is a long-term improvement and is still in development. It is not included in this current *Inventory* report. EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

4.19 Ferroalloy Production (CRT Source Category 2C2)

Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). This reporting category (2C2) includes emissions of carbon dioxide (CO_2) and methane (CH_4) from the production of several ferroalloys. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. Emissions from the production of two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (96 to 99 percent silicon), and miscellaneous alloys (32 to 65 percent silicon) have been calculated.

Emissions from the production of ferrochromium and ferromanganese are not included because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Additionally, production of ferrochromium in the United States ceased in 2009 (USGS 2013a).

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing

[78] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

environment, CO is initially produced and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

While most of the carbon contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Ferroalloys are used to alter the material properties of the steel. Ferroalloys are produced in conjunction with the iron and steel industry, often at co-located facilities, and production trends closely follow that of the iron and steel industry. As of 2020, 11 facilities in the United States produce ferroalloys (USGS 2022b).

Emissions of CO_2 from ferroalloy production in 2022 were 1.3 MMT CO_2 Eq. (1,327 kt CO_2) (see Table 4-97 and Table 4-98), which is a 15 percent reduction since 2021 and a 38 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2022 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4), which is a 15 percent decrease since 2021 and a 45 percent decrease since 1990. Variability in emissions over the past five years is attributable to facility shutdowns in 2018 and 2020 (USGUS 2020; USGS 2021). The latter facility reopened its ferrosilicon production facility in 2021, owing to increased demand for ferrosilicon products and improved domestic pricing (USGS 2022c).

Table 4-97: CO_2 and CH_4 Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2.2	1.4	2.1	1.6	1.4	1.6	1.3
CH_4	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**2.1**	**1.6**	**1.4**	**1.6**	**1.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-98: CO_2 and CH_4 Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2,152	1,392	2,063	1,598	1,377	1,567	1,327
CH_4	1	+	1	+	+	+	+

+ Does not exceed 0.5 kt

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from ferroalloy production are calculated[79] using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual ferroalloy production is multiplied by material-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equations for CO_2 and CH_4 emissions are as follows:

Equation 4-13: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions for Ferroalloy Production (Equation 4.15)

$$E_{CO_2} = \sum_i (MP_i \times EF_i)$$

[79] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with production of ferroalloys did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

where,

E_{CO2} = CO_2 emissions, metric tons

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, metric tons CO_2/metric ton specific ferroalloy product

Equation 4-14: *2006 IPCC Guidelines* Tier 1: CH_4 Emissions for Ferroalloy Production (Equation 4.18)

$$E_{CH_4} = \sum_i (MP_i \times EF_i)$$

where,

E_{CH4} = CH_4 emissions, kg

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, kg CH_4/metric ton specific ferroalloy product

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO_2 and CH_4 estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si: 2.5 metric tons CO_2/metric ton of alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si: 4.0 metric tons CO_2/metric ton alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Silicon Metal: 5.0 metric tons CO_2/metric ton metal produced, 1.2 kg CH_4/metric ton metal produced.

It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke in an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon (C) and 10 percent inert material (Onder and Bagdoyan 1993).

The use of petroleum coke for ferroalloy production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Ferroalloy production data for 1990 through 2022 (see Table 4-99) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2022) and the *Minerals Industry Survey: Silicon* (USGS 2023a). The following data were available from the USGS publications for the time series:

- Ferrosilicon, 25 to 55 percent Si: Annual production data were available from 1990 through 2010.
- Ferrosilicon, 56 to 95 percent Si: Annual production data were available from 1990 through 2010.
- Silicon Metal: Annual production data were available from 1990 through 2005. Production data for 2005 were used as estimates for 2006 through 2010 because data for these years were not available due to government information disclosure rules.
- Miscellaneous Alloys, 32 to 65 percent Si: Annual production data were available from 1990 through 1998. Starting 1999, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS ceased publication of production quantity by ferroalloy product and began reporting all the ferroalloy production data as a single category (i.e., Total Silicon Materials Production). This is due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules. Ferroalloy product shares developed from the 2010 production data (i.e., ferroalloy product production divided by total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2022 (USGS 2017 through 2022).

Table 4-99: Production of Ferroalloys (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Ferrosilicon 25%-55%	321,385	123,000	189,846	147,034	126,681	144,227	122,119
Ferrosilicon 56%-95%	109,566	86,100	167,511	129,736	111,778	127,259	107,752
Silicon Metal	145,744	148,000	183,642	142,229	122,541	139,514	118,128
Misc. Alloys 32-65%	72,442	NA	NA	NA	NA	NA	NA

NA (Not Available) for product type, aggregated with ferrosilicon (25-55% Si)

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Annual ferroalloy production was reported by the USGS in three broad categories until the 2010 publication: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal (through 2005 only, 2005 value used as an estimate for 2006 through 2010). Starting with the *2011 Minerals Yearbook: Silicon*, USGS started reporting all the ferroalloy production under a single category: total silicon materials production. The total silicon materials quantity was allocated across the three categories, based on the 2010 production shares for the three categories. Refer to the Methodology section for further details. Additionally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing proprietary company data. Emissions from this production category, therefore, were not estimated.

Some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants); however, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[80] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available, and are also often considered confidential business information.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging would reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

EPA assigned a uncertainty range of ±25 percent for the primary emission factors (i.e., ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal), and an uncertainty range of ±5 percent for the 2010 production values for ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal production and the 2021 total silicon materials production value used to calculate emissions from overall ferroalloy production. Using these suggested uncertainties provided in in Table 4.9 of Section 4.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert

[80] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data, and a triangular probability density function was assumed for emission factors.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-100. Ferroalloy production CO_2 emissions from 2022 were estimated to be between 1.2 and 1.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 1.3 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 13 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-100: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.3	1.2	1.5	-13%	+13%
Ferroalloy Production	CH_4	+	+	+	-12%	+13%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

Pending available resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC procedures for the Ferroalloy Production source category. Given the small number of facilities and reporting thresholds, particular attention will be made to ensure completeness and time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[81] This is a long-term planned improvement, and EPA is still assessing the possibility of incorporating this improvement into the *Inventory*. This improvement has not been included in the current *Inventory* report.

[81] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.20 Aluminum Production (CRT Source Category 2C3)

Aluminum is a lightweight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of recent reporting, the United States was the ninth[82] largest producer of primary aluminum with an estimated aluminum production of 860 thousand metric tons, with approximately 1.2 percent of the world total production (USGS 2022). The United States was also a major importer of primary aluminum. This reporting category (2C3) includes emissions from the production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Héroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon (C) lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, most of this carbon is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 1.4 MMT CO_2 Eq. (1,446 kt) in 2022 (see Table 4-101 and Table 4-102). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke and is accounted for here and not under the CO_2 from fossil fuel combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-101: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4

Table 4-102: CO_2 Emissions from Aluminum Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed High Voltage Anode Effects (HVAEs). HVAEs cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase. Another type of anode effect, Low Voltage Anode Effects (LVAEs), became a concern in the early 2010s as the aluminum industry increasingly began to use cell technologies with higher amperage and additional anodes (IPCC 2019). LVAEs emit CF_4 and are included in PFC emission totals from 2006 forward.

Since 1990, emissions of CF_4 and C_2F_6 have both declined by 96 and 97 percent respectively, to 0.62 MMT CO_2 Eq.

[82] Based on the U.S. USGS (2022) Aluminum factsheet, assuming all countries grouped under the "other countries" categories all have lower production than the U.S. Available at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-aluminum.pdf.

of CF_4 (0.1 kt) and 0.08 MMT CO_2 Eq. of C_2F_6 (0.01 kt) in 2022, respectively, as shown in Table 4-103 and Table 4-104. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. These actions include technology and operational changes such as employee training, use of computer monitoring, and changes in alumina feeding techniques. Since 1990, aluminum production has declined by 78 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 78 percent. PFC emissions decreased by approximately 18 percent between 2021 and 2022. Aluminum production also decreased in 2022, down 3 percent from 2021.

Table 4-103: PFC Emissions from Aluminum Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	16.1	2.6	1.0	1.1	1.2	0.8	0.7
C_2F_6	3.2	0.5	0.4	0.3	0.2	0.1	0.1
Total	**19.3**	**3.1**	**1.4**	**1.4**	**1.4**	**0.9**	**0.8**

Note: Totals may not sum due to independent rounding.

Table 4-104: PFC Emissions from Aluminum Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	2.4	0.4	0.2	0.2	0.2	0.1	0.1
C_2F_6	0.29	0.05	0.03	0.03	0.02	0.01	0.01

In 2022, U.S. primary aluminum production totaled approximately 0.86 million metric tons, a 3 percent decrease from 2021 production levels (USGS 2023). In 2022, three companies managed production at six operational primary aluminum smelters in five states. Two smelters operated at full capacity during 2022.The other four smelters operated at reduced capacity and one of these four smelters began a temporary shutdown in June (USGS 2023). Domestic smelters were operating at about 52 percent of capacity of 1.64 million tons per year at year end 2022 (USGS 2023).

Methodology and Time-Series Consistency

Process CO_2 and PFC (i.e., CF_4 and C_2F_6) emission estimates from primary aluminum production for 2010 through 2022 are available from EPA's GHGRP Subpart F (Aluminum Production) (EPA 2023). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2022) are available to be incorporated into the *Inventory*. EPA's GHGRP mandates that all facilities that contain an aluminum production process must report: CF_4 and C_2F_6 emissions from anode effects in all prebake and Søderberg electrolysis cells, CO_2 emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO_2 emissions from onsite anode baking. To estimate the process emissions, EPA's GHGRP uses the process-specific equations detailed in Subpart F (aluminum production).[83] These equations are based on the Tier 2/Tier 3 IPCC (2006) methods for primary aluminum production, and Tier 1 methods when estimating missing data elements. It should be noted that the same methods (i.e., *2006 IPCC Guidelines*) were used for estimating the emissions prior to the availability of the reported GHGRP data in the *Inventory*. Prior to 2010, aluminum production data were provided through EPA's Voluntary Aluminum Industrial Partnership (VAIP).

As previously noted, the use of petroleum coke for aluminum production is adjusted for within the Energy chapter to avoid double counting emissions as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the

[83] Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See https://www.ecfr.gov/cgi-bin/text-idx?SID=24a41781dfe4218b339e914de03e8727&mc=true&node=pt40.23.98&rgn=div5#sp40.23.98.f.

Methodology section of CO_2 from Fossil Fuel Combustion (3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels [CRT Source Category 1A]) and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Process CO_2 Emissions from Anode Consumption and Anode Baking

Carbon dioxide emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated using *2006 IPCC Guidelines* methods, but individual facility reported data were combined with process-specific emissions modeling. These estimates were based on information previously gathered from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, U.S. Geological Survey (USGS) Mineral Commodity reviews, and The Aluminum Association (USAA) statistics, among other sources. Since pre- and post-GHGRP estimates use the same methodology, emission estimates are comparable across the time series.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the carbon anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all carbon in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a carbon consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This approach avoids substantial errors and discontinuities that could be introduced by reverting to Tier 1 methods for those years. The last approach corresponds to the IPCC Tier 1 method (IPCC 2006) and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, 2007, 2008, and 2009. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, 13 out of 14 operating smelters in 2006, 5 out of 14 operating smelters in 2007 and 2008, and 3 out of 13 operating smelters in 2009. For years where CO_2 emissions data or CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., previously reported or industry default) values.

In the absence of any previous historical smelter-specific process data (i.e., 1 out of 13 smelters in 2009; 1 out of 14 smelters in 2006, 2007, and 2008; 1 out of 15 smelters in 2005; and 5 out of 23 smelters between 1990 and

2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

High Voltage Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2022 were reported to EPA under its GHGRP. To estimate their PFC emissions from HVAEs and report them under EPA's GHGRP, smelters use an approach identical to the Tier 3 approach in the *2006 IPCC Guidelines* (IPCC 2006). Specifically, they use a smelter-specific slope coefficient as well as smelter-specific operating data to estimate an emission factor using the following equation:

$$PFC = S \times AE$$

$$AE = F \times D$$

where,

PFC = CF_4 or C_2F_6, kg/MT aluminum

S = Slope coefficient, PFC/AE

AE = Anode effect, minutes/cell-day

F = Anode effect frequency per cell-day

D = Anode effect duration, minutes

They then multiply this emission factor by aluminum production to estimate PFC emissions from HVAEs. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

Perfluorocarbon emissions for the years prior to 2010 were estimated using the same equation, but the slope-factor used for some smelters was technology-specific rather than smelter-specific, making the method a Tier 2 rather than a Tier 3 approach for those smelters. Emissions and background data were reported to EPA under the VAIP. For 1990 through 2009, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 94 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP to estimate emission factors over time. For 1990 through 2009, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., previously reported or industry averages) were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2009, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS, and then allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions (see Table 1-5).

Table 4-105: Summary of HVAE Emissions (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HVAE Emissions	19.3	3.1	1.4	1.4	1.4	0.9	0.7

Low Voltage Anode Effects

LVAE emissions of CF_4 were estimated for 2006 through 2022 (see Table 1-6) based on the Tier 1 (technology-specific, production-based) method in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019). Prior to 2006, LVAE emissions are believed to have been negligible.[84] The Tier 1 method is used in the LVAE emissions calculations from aluminum production in the absence of smelter-specific data available to quantify the LVAE-specific process emissions. National aluminum production estimates (allocated to smelters as described below) and the technology used in individual smelters were the best available data to perform the emissions calculations, as smelter-specific production data is not publicly available.

The following equation was used to estimate LVAE PFC emissions:

Equation 4-15: CF_4 Emissions Resulting from Low Voltage Anode Effects

$$LVAE\ E_{CF4} = LVAE\ EF_{CF4} \times MP$$

where,

LVAE E_{CF4} = LVAE emissions of CF_4 from aluminum production, kg CF_4

LVAE EF_{CF4} = LVAE emission factor for CF_4 (default by cell technology type)

MP = Metal production by cell technology type, tons Al.

In the LVAE emissions calculations, the Metal Production (MP) factor is calculated differently for the years 2006 through 2009 than for 2010 and beyond. For years prior to GHGRP reporting (2006 through 2009), the MP factor is calculated by dividing the annual production reported by USGS with the total U.S. capacity reported for this specific year, based on the USGS yearbook and applying this national utilization factor to each facility's production capacity to obtain an estimated facility production value. For GHGRP reporting years (2010+), the methodology to calculate the MP value was changed to allocate the total annual production reported by USAA, based on the distribution of CO_2 emissions amongst the operating smelters in a specific year. The latter improves the accuracy of the LVAE emissions estimates over assuming capacity utilization is the same at all smelters. The main drawback of using this methodology to calculate the MP factor is that, in some instances, it led to production estimates that are slightly larger (less than six percent) than the production capacity reported that year. In practice, this is most likely explained by the differences in process efficiencies at each facility and to a lesser extent, differences in measurements and methods used by each facility to obtain their CO_2 estimates and the degree of uncertainty in the USGS annual production reporting.

Once LVAE emissions were estimated, they were then combined with HVAE emissions estimates to calculate total PFC emissions from aluminum production.

Table 4-106: Summary of LVAE Emissions (MMT CO_2 Eq.)

Year	2006	2018	2019	2020	2021	2022
LVAE Emissions	0.13	0.05	0.07	0.06	0.05	0.05

Production Data

Between 1990 and 2009, production data were provided under the VAIP by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on

[84] The *2019 Refinement* states, "Since 2006, the global aluminum industry has undergone changes in technology and operating conditions that make LVAE emissions much more prevalent[12]; these changes have occurred not only through uptake of newer technologies (e.g., $PFPB_L$ to $PFPB_M$) but also during upgrades within the same technology in order to maximize productivity and reduce energy use" (IPCC 2019). Footnote #12 uses the example of $PFPB_L$, which is prevalent in the United States, as an older technology that has been upgraded.

the difference between reporting smelters and national aluminum production levels as reported to USGS, with allocation to specific smelters based on reported production capacities (USGS 1990 through 2009).

National primary aluminum production data for 2010 through 2022 were compiled using USGS Mineral Industry Surveys, and the USGS Mineral Commodity Summaries (see Table 1-7).

Table 4-107: Production of Primary Aluminum (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	4,048	2,481	891	1,093	1,012	889	860

Methodological approaches were applied to the entire time-series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty was estimated for the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP, taking into consideration the uncertainties associated with aluminum production, anode effect minutes, and slope factors. The uncertainty bounds used for these parameters were established based on information collected under the VAIP and held constant through 2022. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6 emission values were determined to have a normal distribution with uncertainty ranges of approximately 6 percent below to 6 percent above, 16 percent below to 16 percent above, and 20 percent below to 20 percent above their 2022 emission estimates, respectively.

For LVAE, since emission values were not reported through EPA's GHGRP but estimated instead through a Tier 1 methodology, the uncertainty analysis examined uncertainty associated with primary capacity data as well as technology-specific emission factors. Uncertainty for each facility's primary capacity, reported in the USGS Yearbook, was estimated to have a Pert Beta distribution with an uncertainty range of 7 percent below to 7 percent above the capacity estimates based on the uncertainty of reported capacity data, the number of years since the facility reported new capacity data, and uncertainty in capacity utilization. Uncertainty was applied to LVAE emission factors according to technology using the uncertainty ranges provided in the *2019 Refinement to the 2006 IPCC Guidelines*. An uncertainty range for Horizontal Stud Søderberg (HSS) technology was not provided in the *2019 Refinement to the 2006 IPCC Guidelines* due to insufficient data, so a normal distribution and uncertainty range of ±99 percent was applied for that technology based on expert judgment. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2, CF_4, and C_2F_6 emission estimates for the U.S. aluminum industry as a whole, and the results are provided below.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-108. Aluminum production-related CO_2 emissions were estimated to be between 1.41 and 1.48 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3 percent below to 3 percent above the emission estimate of 1.446 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 0.62 and 0.73 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the emission estimate of 0.676 MMT CO_2 Eq. Aluminum production-related C_2F_6 emissions were estimated to be between 0.075 and 0.09 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 0.083 MMT CO_2 Eq. Finally, Aluminum production-related aggregated PFCs emissions were estimated to be between 0.71 and 0.82 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below to 7 percent above the emission estimate of 0.759 MMT CO_2 Eq.

Table 4-108: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	1.446	1.41	1.48	-3%	+3%
Aluminum Production	CF_4	0.676	0.62	0.73	-8%	+8%
Aluminum Production	C_2F_6	0.083	0.075	0.09	-9%	+9%
Aluminum Production	PFCs	0.759	0.71	0.82	-7%	+7%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[85] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 and PFC emissions from aluminum production.

4.21 Magnesium Production and Processing (CRT Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. This reporting category (2C4) includes emissions from magnesium metal production and processing. Sulfur hexafluoride has been used in this application around the world for more than 30 years. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide (CO_2) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride.

[85] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The amount of SF_6 reacting in magnesium production and processing is considered to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 (FK-5-1-12) and dilute sulfur dioxide (SO_2) systems can and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF_6 cover gas systems. Carbon dioxide is also released during primary magnesium production if carbonate based raw materials, such as dolomite, are used. During the processing of these raw materials to produce magnesium, calcination occurs which results in a release of CO_2 emissions.

The magnesium industry emitted 1.1 MMT CO_2 Eq. (0.05 kt) of SF_6, 0.03 MMT CO_2 Eq. (0.02 kt) of HFC-134a, and 0.003 MMT CO_2 Eq. (2.9 kt) of CO_2 in 2022. This represents a decrease of approximately 4 percent from total 2021 emissions (see Table 4-109 and Table 4-110) and a decrease in SF_6 emissions by 3 percent. In 2022, total HFC-134a emissions decreased from 0.040 MMT CO_2 Eq. to 0.029 MMT CO_2 Eq., or a 28 percent decrease as compared to 2021 emissions. FK 5-1-12 emissions in 2022 were consistent with 2021. The emissions of the carrier gas, CO_2, increased from 2.91 kt in 2021 to 2.94 kt in 2022, or 1 percent.

Table 4-109: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	5.6	3.0	1.1	0.9	0.9	1.2	1.1
HFC-134a	0.0	0.0	0.1	0.1	0.1	+	+
CO_2	0.1	+	+	+	+	+	+
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*
Total	**5.7**	**3.0**	**1.1**	**1.0**	**0.9**	**1.2**	**1.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions of FK 5-1-12 are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 4-110: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.2	0.1	+	+	+	+	+
HFC-134a	0.0	0.0	0.1	+	+	+	+
CO_2	129.0	3.6	1.6	2.4	3.0	2.9	2.9
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*

+ Does not exceed 0.5 kt

[a] Emissions of FK 5-1-12 are not included in totals.

Methodology and Time-Series Consistency

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry as well as emissions data reported through Subpart T (Magnesium Production and Processing) of EPA's GHGRP. The Partnership started in 1999 and, in 2010, participating companies represented 100 percent of U.S. primary and secondary production and 16 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). SF_6 emissions for 1999 through 2010 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF_6 consumption, which is assumed to be equivalent to emissions. Along with SF_6, some Partners reported their HFC-134a and FK 5-1-12 consumed, which is also assumed to be equal to emissions. The last reporting year under the Partnership was 2010. Emissions data for 2011 through 2020 are obtained through EPA's GHGRP. Under the program, owners or operators of facilities that have a magnesium production or casting process must report emissions from use of cover or carrier gases, which include SF_6, HFC-134a, FK 5-1-12 and CO_2. Consequently, cover and carrier gas emissions from magnesium

production and processing were estimated for three time periods, depending on the source of the emissions data: 1990 through 1998 (pre-EPA Partnership), 1999 through 2010 (EPA Partnership), and 2011 through 2022 (EPA GHGRP). The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS) as available.

1990 through 1998

To estimate emissions for 1990 through 1998, industry SF_6 emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. For this period, it was assumed that there was no use of HFC-134a or FK 5-1-12 cover gases, and hence emissions were not estimated for these alternatives.

Sulfur hexafluoride emission factors from 1990 through 1998 were based on a number of sources and assumptions. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995. The primary production emission factors were 1.2 kg SF_6 per metric ton for 1990 through 1993, and 1.1 kg SF_6 per metric ton for 1994 through 1997. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average Partner value. An emission factor for die casting of 4.1 kg SF_6 per metric ton, which was available for the mid-1990s from an international survey (Gjestland and Magers 1996), was used for years 1990 through 1996. For 1996 through 1998, the emission factor for die casting was assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that was reported in the RAND survey of major SF_6 manufacturers, which showed a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 1990 through 2001 were assumed to be the same as the 2002 emission factor for all but one facility, which used an emission factor derived from 2011 GHGRP data and held constant to back cast emissions for 1990-1998. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-110. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

The quantities of CO_2 carrier gas used for each production type have been estimated using the 1999 estimated CO_2 emissions data and the annual calculated rate of change of SF_6 use in the 1990 through 1999 time period. For each year and production type, the rate of change of SF_6 use between the current year and the subsequent year was first estimated. This rate of change was then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year.

Carbon dioxide emissions from the calcination of dolomite in the primary production of magnesium were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the estimated primary production of magnesium by an emissions factor of 3.62 kilogram of CO_2 per kilogram of magnesium produced.[86] For 1990 through 1998, production was estimated to be equal to the production capacity of the facility.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production were based on information provided by EPA's industry Partners. In some instances, there were years of missing Partner data, including SF_6 consumption and metal processed. For these situations, emissions were estimated through interpolation where possible, or by holding company-reported emissions (as well as production) constant from the previous year. For alternative cover gases, including HFC-134a and FK 5-1-12, mainly reported data was relied upon. That is, unless a Partner reported using an alternative cover gas, it was not assumed it was used. Emissions of alternate gases were also estimated through linear interpolation where possible.

[86] See https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_4_Ch4_Metal_Industry.pdf.

The die casting emission estimates for 1999 through 2010 were also based on information supplied by industry Partners. When a Partner was determined to be no longer in production, its metal production and usage rates were set to zero. Missing data on emissions or metal input was either interpolated or held constant at the last available reported value. In 1999 through 2010, Partners were assumed to account for all die casting tracked by USGS. For 1999, die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. This emission factor was developed using magnesium production and SF_6 usage data for the year 1999. In 2008, the derived emission factor for die casting began to increase after many years of largely decreasing emission factors. As determined through an analysis of activity data reported from the USGS, this increase is due to a temporary decrease in production at many facilities between 2008 and 2010, which reflects the change in production that occurred during the recession.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF_6 per metric ton of metal produced or processed) by the amount of metal produced or consumed from USGS, with the exception of some years for which Partner sand casting emissions data are available. The emission factors for sand casting activities were acquired through the data reported by the Partnership for 2002 to 2006. For 1999 through 2001, the sandcasting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sandcasting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to a non GHGRP sand casters. Activity data for 2005 was obtained from USGS (USGS 2005b). One non partner sand casting facility reported to GHGRP in 2011 and had an emission factor derived for 2011, this factor was used to back cast emissions for this facility from 1999 to 2010.

The emission factors for primary production, secondary production and sand casting for the 1999 to 2010 are not published to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives. The emission factors for casting activities are provided below in Table 4-111.

The emissions of HFC-134a and FK-5-1-12 were included in the estimates for only instances where Partners reported that information to the Partnership. Emissions of these alternative cover gases were not estimated for instances where emissions were not reported.

Carbon dioxide carrier gas emissions were estimated using the emission factors developed based on GHGRP-reported carrier gas and cover gas data, by production type. It was assumed that the use of carrier gas, by production type, is proportional to the use of cover gases. Therefore, an emission factor, in kg CO_2 per kg cover gas and weighted by the cover gases used, was developed for each of the production types. GHGRP data, on which these emissions factors are based, was available for primary, secondary, die casting and sand casting. The emission factors were applied to the quantity of all cover gases used (SF_6, HFC-134a, and FK-5-1-12) by production type in this time period for producers that reported CO_2 emissions from 2011-2022 through the GHGP. Carrier gas emissions for the 1999 through 2010 time period were only estimated for those Partner companies that reported using CO_2 as a carrier gas through the GHGRP. Using this approach helped ensure time-series consistency. Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using the ratio of total CO_2 emissions to total cover gas emissions for primary, secondary, die and sand in a given year and the total SF_6 emissions from each permanent mold, wrought, and anodes processes respectively in that same year. CO_2 emissions from the calcination of dolomite were estimated using the same approach as described above. At the end of 2001, the sole magnesium production plant operating in the United States that produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions ceased its operations (USGS 1995b through 2023).

Table 4-111: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	1.75[b]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.79	2	1	1
2005	0.77	2	1	1
2006	0.88	2	1	1
2007	0.64	2	1	1
2008	0.97	2	1	1
2009	1.41	2	1	1
2010	1.43	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000 through 2010), Partners made up 100 percent of die casters in the United States.

[b] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2022

For 2011 through 2022, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For sand and die casting, some emissions data was obtained through EPA's GHGRP. Additionally, in 2018 a new GHGRP reporter began reporting permanent mold emissions. The balance of the emissions for this industry segment was estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF_6 at the last reported level, which was from 2010 in most cases, unless publicly available sources indicated that these facilities have closed or otherwise eliminated SF_6 emissions from magnesium production (ARB 2015). Many Partners that did report through the GHGRP showed increases in SF_6 emissions driven by increased production related to a continued economic recovery after the 2008 recession. One Partner in particular reported an anonymously large increase in SF_6 emissions from 2010 to 2011, further driving increases in emissions between the two time periods of inventory estimates. All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above, i.e., non-partner emission factors. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS (USGS 1995b-2023). USGS data for 2022 were not yet available at the time of the analysis, so the 2021 values were held constant through 2022 as an estimate.

Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using an approach consistent with the 1999 through 2010 time series.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. 2006 IPCC Guidance methodologies were used throughout the time series, mainly either a Tier 2 or Tier 3 approach depending on available data.

Uncertainty

Uncertainty surrounding the total estimated emissions in 2022 is attributed to the uncertainties around SF_6, HFC-134a, and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2022 SF_6 emissions from

magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2022 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2022 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation (per the *2006 IPCC Guidelines*). The uncertainty of the total inventory estimate remained relatively constant between 2021 and 2022.

Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-111). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-112. Total emissions associated with magnesium production and processing were estimated to be between 1.06 and 1.24 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7.9 percent below to 7.7 percent above the 2022 emission estimate of 1.15 MMT CO_2 Eq. The uncertainty estimates for 2022 are slightly higher to the uncertainty reported for 2021 in the previous *Inventory*. This increase in uncertainty is attributed to the increased number of facilities with interpolated emissions and the increasing number of years for facilities with emissions held constant.

Table 4-112: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	1.2	1.1	1.2	-7.9%	+7.7%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the

introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[87] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

One die casting facility which had previously had emissions back cast at a constant level had its back casting methodology updated using linear growth from 0 to reported emissions levels between 2001 and 2014, resulting in decreases in SF_6 emissions across 2001 to 2013.

Sand Casting Emissions for 2021 were updated based on 2021 specific data available in the 2021 data tables release from USGS's Mineral Yearbook. 2021 data was previously held constant at 2020 levels due to USGS Mineral Yearbook data only going through 2020. The updated production of sand cast magnesium was larger than what was estimated for 2021 in the previous *Inventory* cycle leading to an increase in SF_6 emissions in 2021.

One sand casting facility, which had previously only been estimated from 2011 onward, was confirmed to have emissions across the time series, an updated emission factor for 2011 was calculated and used to back cast emissions from 1990 to 2010.

Review of facility responses indicate that changes over time in the emission factors for this industry have occurred as facilities switch to using systems with cover gases other than SF_6 (e.g. SO_2) and also during time-periods where back-up SF_6-based systems are used due to the failure of the primary (non-SF_6) system have occurred, leading to the periodic spike in SF_6 usage rates.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the *Inventory* methodology.

Additional emissions are generated as byproducts from the use of alternate cover gases, which are not currently accounted for. Research on this topic is developing, and as reliable emission factors become available, these emissions will be incorporated into the *Inventory.*

4.22 Lead Production (CRT Source Category 2C5)

In 2022, lead was produced in the United States using only secondary production processes. Until 2014, lead production in the United States involved both primary and secondary processes—both of which emit carbon

[87] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

dioxide (CO_2) (Sjardin 2003). This reporting category (2C5) includes emissions from the production of lead. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lead are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the end of 2013, and a small amount of residual lead was processed during demolition of the facility in 2014 (USGS 2015). Beginning in 2015, primary lead production no longer occurred in the United States.

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Secondary lead production in the United States has fluctuated over the past 20 years, reaching a high of 1,180,000 metric tons in 2007 and again in 2019. In 2022, secondary lead production accounted for 100 percent of total U.S. lead production. The lead-acid battery industry accounted for about 92 percent of the reported U.S. lead consumption in 2022 (USGS 2023a).

In 2022, secondary lead production in the United States decreased by approximately 3 percent compared to 2021 (USGS 2023a). Secondary lead production in 2022 is 3 percent higher than in 1990 (USGS 1994 and 2023a). The United States has become more reliant on imported refined lead, owing to the closure of the last primary lead smelter in 2013. Exports of spent starting-lighting-ignition (SLI) batteries decreased between 2014 and 2017, and subsequently recovered beginning in 2018. Exports were 10 percent higher in the first 9 months of 2021 compared to the same time period in 2014 (USGS 2015 through 2023b). In the first 9 months of 2022, 24.6 million spent SLI lead-acid batteries were exported, 4 percent less than that in the same time period in 2021 (USGS 2023b).

Emissions of CO_2 from lead production in 2022 were 0.4 MMT CO_2 Eq. (428 kt), which is a 3 percent decrease compared to 2021 and a 17 percent decrease compared to 1990 (see Table 4-113 and Table 4-114) (USGS 1994; USGS 2023a; USGS 2023b).

The United States was the third largest mine producer of lead in the world, behind China and Australia, and accounted for approximately 6 percent of world production in 2022 (USGS 2023a).

Table 4-113: CO_2 Emissions from Lead Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4

Table 4-114: CO_2 Emissions from Lead Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	516	553	527	531	450	439	428

Methodology and Time-Series Consistency

Carbon dioxide emissions from lead production[88] are calculated based on Sjardin's work (Sjardin 2003) for lead production emissions and use Tier 1 methods from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-16: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions From Lead Production (Equation 4.32)

$$CO_2\ Emissions = (DS\ \times EF_{DS})\ + (S\ \times EF_S)$$

where,

DS	=	Lead produced by direct smelting, metric ton
S	=	Lead produced from secondary materials
EF_{DS}	=	Emission factor for direct smelting, metric tons CO_2/metric ton lead product
EF_S	=	Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The production and use of coking coal for lead production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

The 1990 through 2022 activity data for primary and secondary lead production (see Table 4-115) were obtained from the U.S. Geological Survey (USGS 1994 through 2023a).

Table 4-115: Lead Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	404,000	143,000	0	0	0	0	0
Secondary	922,000	1,150,000	1,170,000	1,180,000	1,000,000	975,000	950,000

Methodological approaches discussed below were applied to applicable years to ensure time-series consistency in emissions from 1990 through 2022.

[88] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Lead Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

Uncertainty

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000; Morris et al. 1983; Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. EPA assigned an uncertainty range of ±20 percent for these emission factors, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for a Tier 1 emission factor by process type is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assumed for emission factors.

There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS which is collected via voluntary surveys; the uncertainty of the activity data is a function of the reliability of reported plant-level production data and the completeness of the survey response. EPA currently uses an uncertainty range of ±10 percent for primary and secondary lead production, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for Tier 1 national production data is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-116. Lead production CO_2 emissions in 2022 were estimated to be between 0.4 and 0.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below and 16 percent above the emission estimate of 0.4 MMT CO_2 Eq.

Table 4-116: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.4	0.4	0.5	-15%	+16%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Initial review of activity data show that EPA's GHGRP Subpart R lead production data and resulting emissions are fairly consistent with those reported by USGS. EPA is still reviewing available GHGRP data, reviewing QC analysis to understand differences in data reporting (i.e., threshold implications), and assessing the possibility of including this planned improvement in future *Inventory* reports (see Planned Improvements section below). Currently, GHGRP data are used for QA purposes only.

Recalculations Discussion

Recalculations were implemented for 2020 and 2021 based on revised USGS data for secondary lead production. Compared to the previous *Inventory*, emissions decreased by 3 percent (14 kt CO_2) for 2020 and by 2 percent (7 kt CO_2) for 2021 (USGS 2023b).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Lead Production source category, in particular considering completeness of reported lead production given the reporting threshold. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[89]

4.23 Zinc Production (CRT Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes currently used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy carbon dioxide (CO_2) emissions (Viklund-White 2000). This reporting category (2C6) includes emissions from the production of zinc. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of zinc are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, and copper ingot manufacturing). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Production of zinc can be conducted with a range of pyrometallurgical (e.g., electrothermic furnace, Waelz kiln, flame reactor, batch retorts, Pinto process, and PIZO process) and hydrometallurgical (e.g., hydrometallurgical recovery, solvent recovery, solvent extraction-electrowinning, and electrolytic) processes. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003). Primary production in the United States is conducted through the non-emissive electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other processes. Worldwide primary zinc production also employs a pyrometallurgical process using an Imperial Smelting Furnace; however, this process is not used in the United States (Sjardin 2003).

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

[89] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \quad \text{(Reaction 2)}$$

In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1,100 to 1,200 degrees Celsius, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

In the flame reactor process, a waste feed stream, which can include EAF dust, is processed in a high-temperature environment (greater than 2,000 °C) created by the combustion of natural gas or coal and oxygen-enriched air. Volatile metals, including zinc, are forced into the gas phase and drawn into a combustion chamber, where air is introduced and oxidation occurs. The metal oxide product is then collected in a dust collection system (EPA 1992).

In 2022, the only companies in the United States that used emissive technology to produce secondary zinc products were Befesa Holding US Inc (Befesa) and Steel Dust Recycling (SDR). The secondary zinc facilities operated by Befesa were acquired from American Zinc Recycling (AZR) (formerly "Horsehead Corporation") in 2021. PIZO Operating Company, LLC (PIZO) operated a secondary zinc production facility that processed EAF dust in Blytheville, AR from 2009 to 2012.

For Befesa, EAF dust is recycled in Waelz kilns at their Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. The former AZR facility in Beaumont, TX processed EAF dust via flame reactor from 1993 through 2009 (AZR 2021, Horsehead 2014). These Waelz kiln and flame reactor facilities produce intermediate zinc products (crude zinc oxide or calcine). Prior to 2014, most of output from these facilities were transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, the Monaca smelter was permanently closed and replaced by a new facility in Mooresboro, NC in 2014.

The Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products, which is assumed to be non-emissive as described above. Production at the Mooresboro facility was idled in April 2016 and re-started in March 2020 (Recycling Today 2020). Direct consumption of coal, coke, and natural gas were replaced with electricity consumption (Horsehead 2012b). The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015).

SDR recycles EAF dust into intermediate zinc products using Waelz kilns and sells the intermediate products to companies who smelt it into refined products.

Emissions of CO_2 from zinc production in 2022 were estimated to be 0.9 MMT CO_2 Eq. (947 kt CO_2) (see Table 4-117). All 2022 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the United States have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2022, emissions were estimated to be 50 percent higher than they were in 1990. Emissions decreased 6 percent from 2021 levels.

Table 4-117: CO_2 Emissions from Zinc Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9

Table 4-118: CO_2 Emissions from Zinc Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	632	1,030	999	1,026	977	1,007	947

U.S. zinc mine production increased by 9 percent in 2022 compared to 2021, due in part to higher mill throughput and zinc ore grades at the Red Dog Mine in Alaska, the largest zinc mine in the United States. In 2022, United States primary and secondary refined zinc production were estimated to total 220,000 metric tons (USGS 2023) (see Table 4-119), remaining at approximately the same production level as in 2021. Secondary zinc production fell to its lowest point in the time series in 2019, following the closure of the Monaca, PA smelter in 2014 and issues with the AZR secondary zinc refinery in Mooresboro, NC. Secondary zinc production has increased significantly since the reopening of the idled Mooresboro facility in March 2020 (USGS 2021; AZP 2021).

Table 4-119: Zinc Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	262,704	191,120	101,000	101,000	101,000	101,000	101,000
Secondary	95,708	156,000	15,000	14,000	79,000	119,000	119,000
Total	**358,412**	**347,120**	**116,000**	**115,000**	**180,000**	**220,000**	**220,000**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 emissions from zinc production[90] using the electrothermic primary production and Waelz kiln secondary production processes are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

Equation 4-17: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Zinc Production (Equation 4.33)

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO_2} = CO_2 emissions from zinc production, metric tons

Zn = Quantity of zinc produced, metric tons

$EF_{default}$ = Default emission factor, metric tons CO_2/metric ton zinc produced

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from metallurgical coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the United States used hydrometallurgical processes and is assumed to be non-emissive.

[90] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Zinc Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities, while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

Equation 4-18: Waelz Kiln CO_2 Emission Factor for Zinc Produced

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

Refined zinc production levels for AZR's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and replaced by AZR's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

Metallurgical coke consumption for non-EAF dust consuming facilities for 1990 through 2004 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States, as provided by the U.S. Geological Survey (USGS) *Minerals Yearbook: Zinc* (USGS 1994 through 2006). Metallurgical coke consumption for 2005 through 2013 were based on the secondary zinc production values obtained from the Horsehead Corporation Annual Report Form 10-K: 2005 through 2008 from the 2008 10-K (Horsehead Corp 2009); 2009 and 2010 from the 2010 10-K (Horsehead Corp. 2011); and 2011 through 2013 from the associated 10-K (Horsehead Corp. 2012a, 2013, 2014). Metallurgical coke consumption levels for 2014 and later were zero due to the closure of the AZR (formerly "Horsehead Corporation") electrothermic furnace facility in Monaca, PA. The secondary zinc produced values for each year were then multiplied by the 3.70 metric tons CO_2/metric ton zinc produced emission factor to develop CO_2 emission estimates for the AZR electrothermic furnace facility.

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

Equation 4-19: Waelz Kiln CO_2 Emission Factor for EAF Dust Consumed

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

Metallurgical coke consumption for EAF dust consuming facilities for 1990 through 2022 were calculated based on the values of EAF dust consumed. The total amount of EAF dust consumed by the Waelz kilns currently operated by Befesa was available from AZR (formerly "Horsehead Corporation") in financial reports for years 2006 through 2015 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, 2015, and 2016), from correspondence with AZR for 2016 through 2019 (AZR 2020), and from correspondence with Befesa for 2020 through 2022 (Befesa 2022, 2023). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for Befesa's Waelz kiln facilities.

The amount of EAF dust consumed by SDR and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2022 (SDR 2012, 2014, 2015, 2017, 2018, 2021, 2022, 2023). The SDR facility has been operational since 2008, underwent expansion in 2011 to include a second unit (operational since early- to mid-2012), and expanded its capacity again in 2017 (SDR 2018). Annual consumption data for SDR was not publicly

available for the years 2008, 2009, and 2010. These data were estimated using data for AZR's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, 2011). Annual capacity utilization ratios were calculated using AZR's annual consumption and total capacity for the years 2008 through 2010. AZR's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to SDR's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

PIZO's facility in Arkansas was operational from 2009 to 2012 (PIZO 2021). The amount of EAF dust consumed by PIZO's facility for 2009 through 2012 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of AZR's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2012 were estimated by applying the average annual capacity utilization rates for AZR and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012; SDR 2012; PIZO 2012). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

The production and use of coking coal for zinc production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Beginning with the 2017 USGS *Minerals Commodity Summary: Zinc*, United States primary and secondary refined zinc production were reported as one value, total refined zinc production. Prior to this publication, primary and secondary refined zinc production statistics were reported separately. For years 2016 through 2022, only one facility produced primary zinc. Primary zinc produced from this facility was subtracted from the USGS 2016 to 2022 total zinc production statistic to estimate secondary zinc production for these years.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

There is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on combining the totals for (1) the EAF dust consumption value obtained for the kilns currently operated by Befesa (and formerly operated by AZR or Horsehead Corporation) and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated by SDR. For the 1990 through 2015 estimates, EAF dust consumption values for the kilns currently operated by Befesa were obtained from annual financial reports to the Securities and Exchange Commission (SEC) by AZR. In 2016, AZR reorganized as a private company and ceased providing annual reports to the SEC (Recycling Today 2017). EAF dust consumption values for subsequent years from the Befesa kilns and SDR have been obtained from personal communication with facility representatives. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for AZR (which was available from Horsehead Corporation financial reports).The EAF dust consumption for PIZO's facility for 2011 through 2012 was estimated by multiplying the average capacity utilization factor developed from AZR and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO's annual EAF dust consumption values for 2009 through 2012 and SDR's annual EAF dust consumption values for 2008 through 2010. EPA uses an uncertainty range of ±5 percent for these EAF dust consumption data inputs, based upon expert elicitation from the USGS commodity specialist. Per this expert judgment, a normal probability density function was assigned for EAF dust consumption data inputs.

There is also uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depends upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes. Consistent with the ranges in Table 4.25 of the *2006 IPCC Guidelines*, EPA assigned an uncertainty range of ±20 percent for the Tier 1 Waelz kiln emission factors, which are provided by Viklund-White in the form of metric tons of coke per metric ton of EAF dust consumed and metric tons of coke per metric ton of zinc produced. In order to convert coke consumption rates to CO_2 emission rates, values for the heat and carbon content of coke were obtained from Table 4.2 – Tier 2 of the *2006 IPCC Guidelines*. An uncertainty range of ±10 percent was assigned to these coke data elements, and using the suggested uncertainty provided in Table 4.25, Tier 2 – National Reducing Agent & Process Materials Data of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors and the heat and carbon content of coke.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-120. Zinc production CO_2 emissions from 2022 were estimated to be between 0.8 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-120: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	0.9	0.8	1.1	-18%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for the year 2021 based on updated EAF dust consumption data. Compared to the previous *Inventory*, 2021 emissions from zinc production increased by 4 percent (38 kt CO_2).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for zinc production, in particular considering completeness of reported zinc production given the reporting threshold. Given the small number of facilities in the United States, particular attention will be made to risks for disclosing CBI and ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing

improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[91] This is a long-term planned improvement, and EPA is still assessing the possibility of including this improvement in future *Inventory* reports.

4.24 Electronics Industry (CRT Source Category 2E)

The electronics industry uses multiple greenhouse gases in its manufacturing processes. In semiconductor manufacturing, these include long-lived fluorinated greenhouse gases used for plasma etching and chamber cleaning (CRT Source Category 2E1), fluorinated heat transfer fluids used for temperature control and other applications (CRT Source Category 2E4), and nitrous oxide (N_2O) used to produce thin films through chemical vapor deposition and in other applications (reported under CRT Source Category 2H3). Similar to semiconductor manufacturing, the manufacturing of micro-electro-mechanical systems (MEMS) devices (reported under CRT Source Category 2E5 Other) and photovoltaic (PV) cells (CRT Source Category 2E3) requires the use of multiple long-lived fluorinated greenhouse gases for various processes.

The gases most commonly employed in the electronics industry are trifluoromethane (hydrofluorocarbon (HFC)-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other fluorinated compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

In addition to emission estimates for these seven commonly used fluorinated gases, this *Inventory* contains emissions estimates for N_2O and other HFCs and unsaturated, low-GWP PFCs including C_5F_8, C_4F_6, HFC-32, HFC-41, and HFC-134a. These additional HFCs and PFCs are emitted from etching and chamber cleaning processes in much smaller amounts, accounting for 0.02 percent of emissions (in CO_2 Eq.) from these processes.

For semiconductors, a single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. Plasma enhanced chemical vapor deposition (PECVD) chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is typically generated and emitted as a process byproduct. In some cases, emissions of the byproduct gas can rival or even exceed emissions of the input gas, as is the case for NF_3 used in remote plasma chamber cleaning, which often generates CF_4 as a byproduct.

[91] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

Liquid perfluorinated compounds are also used as heat transfer fluids (F-HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions (EPA 2006). Unweighted F-HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers (specifically, PFPMIEs), and perfluoroalkylmorpholines. Three percent or less consist of HFCs, PFCs, and SF_6 (where PFCs are defined as compounds including only carbon and fluorine). With the exceptions of the hydrofluoroethers and most of the HFCs, all of these compounds are very long-lived in the atmosphere and have global warming potentials (GWPs) near 10,000.[92]

MEMS and photovoltaic cell manufacturing require thin film deposition and etching of material with a thickness of one micron or more, so the process is less intricate and complex than semiconductor manufacturing. The manufacturing process is different than semiconductors, but generally employs similar techniques. Like semiconductors, MEMS and photovoltaic cell manufacturers use fluorinated compounds for etching, cleaning reactor chambers, and temperature control. CF_4, SF_6, and the Bosch process (which consists of alternating steps of SF_6 and C_4F_8) are used to manufacture MEMS (EPA 2010). Photovoltaic cell manufacturing predominately uses CF_4, to etch crystalline silicon wafers, and C_2F_6 or NF_3 during chamber cleaning after deposition of SiN_x films (IPCC 2006), although other F-GHGs may be used. Similar to semiconductor manufacturing, both MEMS and photovoltaic cell manufacturing use N_2O in depositing films and other manufacturing processes. MEMS and photovoltaic manufacturing may also employ HTFs for cooling process equipment (EPA 2010).

Emissions from all fluorinated greenhouse gases (including F-HTFs) and N_2O for semiconductors, MEMS and photovoltaic cells manufacturing are presented in Table 4-121 below for the years 1990, 2005, and the period 2018 to 2022. The rapid growth of the electronics industry and the increasing complexity (growing number of layers and functions)[93] of electronic products led to an increase in emissions of 152 percent between 1990 and 1999, when emissions peaked at 8.4 MMT CO_2 Eq. Emissions began to decline after 1999, reaching a low point in 2009 before rebounding to 2006 emission levels and more or less plateauing at the current level, which represents a 44 percent decline from 1999 to 2022. Together, industrial growth, adoption of emissions reduction technologies (including but not limited to abatement technologies) and shifts in gas usages resulted in a net increase in emissions of approximately 41 percent between 1990 and 2022. Total emissions from semiconductor manufacture in 2022 were lower than 2021 emissions, decreasing by 7.5 percent, largely due to a large decrease in SF_6 emissions. The decrease in SF_6 are seen in facilities that manufacture 200 mm wafer size that do not have abatement systems installed as well as 300 mm wafer size that have abatement systems installed.

For U.S. semiconductor manufacturing in 2022, total CO_2-equivalent emissions of all fluorinated greenhouse gases and N_2O from deposition, etching, and chamber cleaning processes were estimated to be 4.6 MMT CO_2 Eq. This is a

[92] The GWP of PFPMIE, a perfluoropolyether used as an F-HTF, is included in the IPCC *Fourth Assessment Report* with a value of 10,300. The GWPs of the perfluorinated amines and perfluoroalkylmorpholines that are used as F-HTFs have not been evaluated in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (78 FR 20632), which is expected given that these compounds are both saturated and fully fluorinated. EPA assigns a default GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[93] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

decrease in emissions from 1999 of 45 percent, and an increase in emissions from 1990 of 40 percent. These trends are driven by the above stated reasons.

Photovoltaic cell and MEMS manufacturing emissions of all fluorinated greenhouse gases are in Table 4-121. While EPA has developed a simple methodology to estimate emissions from non-reporters and to back-cast emissions from these sources for the entire time series, there is very high uncertainty associated with these emission estimates.

The emissions reported by facilities manufacturing MEMS included emissions of C_2F_6, C_3F_8, c-C_4F_8, CF_4, HFC-23, NF_3, N_2O and SF_6,[94] and were equivalent to only 0.110 percent to 0.264 percent of the total reported emissions from electronics manufacturing in 2011 to 2022. F-GHG emissions, the primary type of emissions for MEMS, ranged from 0.0003 to 0.012 MMT CO_2 Eq. from 1991 to 2022. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing (GHGRP reporters must choose a single classification per fab). Emissions from non-reporters have not been estimated.

Total CO_2-equivalent emissions from manufacturing of photovoltaic cells were estimated to range from 0.0003 MMT CO_2 Eq. to 0.0330 MMT CO_2 Eq. from 1998 to 2022 and were equivalent to between 0.003 percent to 0.77 percent of the total reported emissions from electronics manufacturing. F-GHG emissions, the primary type of emissions for photovoltaic cells, ranged from 0.0003 to 0.032 MMT CO_2 Eq. from 1998 to 2022. Emissions from manufacturing of photovoltaic cells were estimated using an emission factor developed from reported data from a single manufacturer between 2015 and 2016. This emission factor was then applied to production capacity estimates from non-reporting facilities. Reported emissions from photovoltaic cell manufacturing consisted of CF_4, C_2F_6, c-C_4F_8, CHF_3, NF_3, and N_2O.[95]

Emissions of F-HTFs, grouped by HFCs, PFCs or SF_6 are presented in Table 4-121. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only.

Since reporting of F-HTF emissions began under EPA's GHGRP in 2011, total F-HTF emissions (reported and estimated non-reported) have fluctuated between 0.4 MMT CO_2 Eq. and 0.9 MMT CO_2 Eq., with an overall declining trend between 2011 to 2022. An analysis of the data reported to EPA's GHGRP indicates that F-HTF emissions account for anywhere between 9 percent and 17 percent of total annual emissions (F-GHG, N_2O and F-HTFs) from semiconductor manufacturing.[96] Table 4-123 shows F-HTF emissions in tons by compound group based on reporting to EPA's GHGRP and the interpolated share of F-HTF emissions to F-GHG emissions for select years prior to reporting. [97]

[94] Gases not reported by MEMS manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[95] Gases not reported by PV manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[96] Emissions data for HTFs (in tons of gas) from the semiconductor industry from 2011 through 2022 were obtained from the EPA GHGRP annual facility emissions reports.

[97] Many fluorinated heat transfer fluids consist of perfluoropolymethylisopropyl ethers (PFPMIEs) of different molecular weights and boiling points that are distilled from a mixture. "BP 200 °C" (and similar terms below) indicate the boiling point of the fluid in degrees Celsius. For more information, see https://www.regulations.gov/document?D=EPA-HQ-OAR-2009-0927-0276.

Table 4-121: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Electronics Industry (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	0.8	1.0	1.6	1.5	1.6	1.7	1.6
C_2F_6	1.8	1.8	1.1	0.9	0.8	0.9	0.9
C_3F_8	+	0.1	0.1	0.1	0.1	0.1	0.1
C_4F_8	0.0	0.1	0.1	0.1	0.1	0.1	0.1
HFC-23	0.2	0.2	0.3	0.3	0.3	0.4	0.3
SF_6	0.5	0.8	0.8	0.8	0.8	0.9	0.7
NF_3	+	0.4	0.6	0.5	0.6	0.7	0.6
C_4F_6	+	+	+	+	+	+	+
C_5F_8	+	+	+	+	+	+	+
CH_2F_2	+	+	+	+	+	+	+
CH_3F	+	+	+	+	+	+	+
CH_2FCF_3	+	+	+	+	+	+	0
Total Semiconductors	**3.3**	**4.3**	**4.5**	**4.2**	**4.3**	**4.7**	**4.3**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_3F_8	0.0	+	0.0	0.0	0.0	0.0	0.0
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	+	+	+	+	+	+
NF_3	0.0	0.0	+	+	+	+	+
Total MEMS	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NF_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total PV	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (Semiconductors)	+	0.1	0.2	0.2	0.3	0.3	0.3
N_2O (MEMS)	0.0	+	+	+	+	+	+
N_2O (PV)	0.0	+	+	+	+	+	+
Total N_2O	**+**	**0.1**	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**
HFC, PFC and SF_6 F-HTFs	0.0	+	+	+	+	+	+
Total Electronics Industry	**3.3**	**4.5**	**4.8**	**4.4**	**4.5**	**4.8**	**4.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-122: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	114.8	145.3	237.0	221.1	237.4	252.8	240.9
C_2F_6	160.0	163.4	98.7	83.2	76.0	80.0	80.8
C_3F_8	0.4	7.3	12.2	9.9	9.4	11.0	13.4
C_4F_8	0.0	10.9	6.2	5.7	6.1	6.6	5.9
HFC-23	14.6	14.1	26.4	25.6	26.5	32.6	24.9
SF_6	21.7	33.4	33.8	32.8	33.6	39.8	31.1
NF_3	2.8	26.2	34.4	33.5	37.2	40.9	39.1
C_4F_6	0.7	0.9	0.8	0.9	0.8	1.2	0.8
C_5F_8	0.5	0.6	0.5	0.4	0.4	0.4	0.4

CH_2F_2	0.6	0.8	0.9	1.0	1.1	1.1	1.0
CH_3F	1.4	1.8	2.6	2.5	3.1	3.2	2.4
CH_2FCF_3	+	+	+	+	+	+	0.0
N_2O	135.9	463.3	881.5	822.2	1,023.0	1,083.6	1,111.2

+ Does not exceed 0.05 MT.

Table 4-123: F-HTF Emissions from Electronics Manufacture by Compound Group (kt CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HFCs	0.0	0.9	2.7	1.1	0.9	1.2	1.5
PFCs	0.0	3.8	10.0	8.4	8.0	5.7	7.3
SF_6	0.0	5.6	13.2	6.0	13.2	9.4	4.1
HFEs	0.0	39.4	4.6	1.3	5.5	4.0	14.2
PFPMIEs	0.0	110.5	183.3	172.6	154.8	155.4	162.8
Perfluoalkylromorpholines	0.0	66.4	58.5	56.4	62.8	55.9	19.4
Perfluorotrialkylamines	0.0	209.9	414.7	363.8	391.5	382.2	233.5
Total F-HTFs	**0.0**	**436.5**	**687.0**	**608.4**	**636.6**	**613.6**	**443.0**

Notes: Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, semiconductor manufacturing Partner-reported emissions data received through EPA's PFC[98] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions from etching and chamber cleaning processes in the absence of emission control strategies (Burton and Beizaie 2001)[99]—and estimates of industry activity (i.e., total manufactured layer area and manufacturing capacity). The availability and applicability of reported emissions data from the EPA Partnership and EPA's GHGRP and activity data differ across the 1990 through 2022 time series. Consequently, fluorinated greenhouse gas (F-GHG) emissions from etching and chamber cleaning processes for semiconductors were estimated using seven distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. Nitrous oxide emissions were estimated using five distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. The methodology discussion below for these time periods focuses on semiconductor emissions from etching, chamber cleaning, and uses of N_2O. Other emissions for MEMS, photovoltaic cells, and HTFs were estimated using the approaches described immediately below.

MEMS

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of MEMS are available for the years 2011 to 2022. Emissions from manufacturing of MEMS for years prior to 2011 were calculated by linearly interpolating emissions between 1990 (at zero MMT CO_2 Eq.) and 2011, the first year where emissions from manufacturing of MEMS was reported to the GHGRP. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from

[98] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[99] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010.

semiconductor manufacturing; however, emissions from MEMS manufacturing are likely being included in semiconductor totals. Emissions were not estimated for non-reporters.

Photovoltaic Cells

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of photovoltaic cells are available for 2011, 2012, 2015, and 2016 from two manufacturers. EPA estimates the emissions from manufacturing of PVs from non-reporting facilities by multiplying the estimated capacity of non-reporters by a calculated F-GHG emission factor and N_2O emission factor based on GHGRP reported emissions from the manufacturer (in MMT CO_2 Eq. per megawatt) that reported emissions in 2015 and 2016. This manufacture's emissions are expected to be more representative of emissions from the sector, as their emissions were consistent with consuming only CF_4 for etching processes and are a large-scale manufacturer, representing 28 percent of the U.S. production capacity in 2016. The second photovoltaic manufacturer only produced a small fraction of U.S. production (<4 percent). They also reported the use of NF_3 in remote plasma cleaning processes, which does not have an emission factor in Part 98 for PV manufacturing, requiring them to report emissions equal to consumption. The total F-GHG emissions from non-reporters are then disaggregated into individual gases using the gas distribution from the 2015 to 2016 manufacturer. Manufacturing capacities in megawatts were drawn from DisplaySearch, a 2015 Congressional Research Service Report on U.S. Solar Photovoltaic Manufacturing, and self-reported capacity by GHGRP reporters. EPA estimated that during the 2015 to 2016 period, 28 percent of manufacturing capacity in the United States was represented through reported GHGRP emissions. Capacities are estimated for the full time series by linearly scaling the total U.S. capacity between zero in 1997 to the total capacity reported of crystalline silicon (c-Si) PV manufacturing in 2000 in DisplaySearch and then linearly scaling between the total capacity of c-Si PV manufacturing in DisplaySearch in 2009 to the total capacity of c-Si PV manufacturing reported in the Congressional Research Service report in 2012. Capacities were held constant for non-reporters for 2012 to 2019. In 2020, non-reporter capacity declined due to the closure of several PV manufacturing plants. This capacity was held constant for 2021 and 2022. Average emissions per MW from the GHGRP reporter in 2015 and 2016 were then applied to the total capacity prior to 2015. Emissions for 2014 from the GHGRP reporter that reported in 2015 and 2016 were scaled to the number of months open in 2014. For 1998 through 2022, emissions per MW (capacity) from the GHGRP reporter were applied to the non-reporters. For 2017 through 2022, there are no reported PV emissions. Therefore, emissions were estimated using the EPA-derived emission factor and estimated manufacturing capacity from non-reporters only.

HTFs

Facility emissions of F-HTFs from semiconductor manufacturing are reported to EPA under its GHGRP and are available for the years 2011 through 2022. EPA estimates the emissions of F-HTFs from non-reporting semiconductor facilities by calculating the ratio of GHGRP-reported fluorinated HTF emissions to GHGRP reported F-GHG emissions from etching and chamber cleaning processes, and then multiplying this ratio by the F-GHG emissions from etching and chamber cleaning processes estimated for non-reporting facilities. Fluorinated HTF use in semiconductor manufacturing is assumed to have begun in the early 2000s and to have gradually displaced other HTFs (e.g., de-ionized water and glycol) in semiconductor manufacturing (EPA 2006). For time-series consistency, EPA interpolated the share of F-HTF emissions to F-GHG emissions between 2000 (at 0 percent) and 2011 (at 17 percent) and applied these shares to the unadjusted F-GHG emissions during those years to estimate the emissions.

Semiconductors

1990 through 1994

From 1990 through 1994, Partnership data were unavailable, and emissions were modeled using PEVM (Burton

and Beizaie 2001).[100] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of manufactured layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[101] and (2) product type (discrete, memory or logic).[102] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC) specific to product type (Burton and Beizaie 2001; ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions and hence may be use here to estimate 1990 through 1994 emissions. The emission factor is used to estimate U.S. uncontrolled emissions using publicly available data on world (including U.S.) silicon consumption.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

PEVM only addressed the seven main F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, HFC-23, SF_6, and NF_3) used in semiconductor manufacturing. Through reporting under Subpart I of EPA's GHGRP, data on other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) used in semiconductor manufacturing became available and EPA was therefore able to extrapolate this data across the entire 1990 to 2022 timeseries. To estimate emissions for these "other F-GHGs", emissions data from Subpart I between 2014 to 2016 were used to estimate the average share or percentage contribution of these gases as compared to total F-GHG emissions. Subpart I emission factors were updated for 2014 by EPA as a

[100] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[101] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[102] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

result of a larger set of emission factor data becoming available, so reported data from 2011 through 2013 was not utilized for the average. To estimate non-reporter emissions from 2011-2022, the average emissions data from Subpart I of 2011 to 2022 was used.

To estimate N_2O emissions, it was assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through 1994.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM-estimated emissions and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly. Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

For this time period, the N_2O emissions were estimated using an emission factor that was applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on EPA's GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2012 section. The total U.S. TMLA for 1995 through 1999 was estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time-series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor (PEVM emission factor) was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total emissions attributed to non-Partners is obtained by multiplying PEVM's total U.S. emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[103] Gas-specific emissions from non-Partners were estimated using linear interpolation between the gas-specific emissions distributions of 1999 (assumed to be the same as that of the total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partners that reported through the GHGRP as a result of emitting more than 25,000 MT CO_2 Eq. per year). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC

[103] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[104, 105, 106] For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[107] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent figure was assumed (SIA 2009).

In addition, publicly available utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. The Semiconductor Capacity Utilization (SICAS) Reports from SIA provides the global semiconductor industry capacity and utilization, differentiated by discrete and IC products (SIA 2009 through 2011). PEVM estimates were adjusted using technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

---

[104] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2 to 3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFF were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[105] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[106] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[107] EPA considered applying this change to years before 2007 but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

For this time period emissions of other F-GHGs (C_5F_8, CH_2F_2, CH_3F, CH_2FCF_3, $C_2H_2F_4$) were estimated using the method described above for 1990 to 1994. Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2011 through 2012

The fifth method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2012. This methodology differs from previous years because the EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under EPA's GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 MT CO_2 Eq. per year (based on default F-GHG-specific emission factors and total capacity in terms of substrate area) are required to report their emissions to EPA. This population of reporters to EPA's GHGRP included both historical Partners of EPA's PFC Reduction/Climate Partnership as well as non-Partners some of which use gallium arsenide (GaAs) technology in addition to Si technology.[108] Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both reporting and non-reporting populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of F-GHGs (for all types of F-GHGs) used in etch and clean processes as well as emissions of fluorinated heat transfer fluids. (Fluorinated heat transfer fluids are used to control process temperatures, thermally test devices, and clean substrate surfaces, among other applications.) They also report N_2O emissions from CVD and other processes. The F-GHGs and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. At this time, emissions that result from heat transfer fluid use that are HFC, PFC and SF_6 are included in the total emission estimates from semiconductor manufacturing, and these GHGRP-reported emissions have been compiled and presented in Table 4-121. F-HTF emissions resulting from other types of gases (e.g., HFEs) are not presented in semiconductor manufacturing totals in Table 4-121 and Table 4-122 but are shown in Table 4-123 for informational purposes.

Changes to the default emission factors and default destruction or removal efficiencies (DREs) used for GHGRP reporting affected the emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. Therefore, for the current *Inventory*, EPA adjusted the time series of GHGRP-reported data for 2011 through 2013 to ensure time-series consistency using a series of calculations that took into account the characteristics of a facility (e.g., wafer size and abatement use). To adjust emissions for facilities that did not report abatement in 2011 through 2013, EPA simply applied the revised emission factors to each facility's estimated gas consumption by gas, process type and wafer size. In 2014, EPA also started collecting information on fab-wide DREs and the gases abated by process type, which were used in calculations for adjusting emissions from facilities that abated F-GHGs in 2011 through 2013.

- To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first calculated the quantity of gas abated in 2014 using reported F-GHG emissions, the revised default DREs (or the estimated site-specific DRE,[109] if a site-specific DRE was indicated), and the fab-wide DREs reported in 2014.[110] To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first estimated

[108] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[109] EPA generally assumed site-specific DREs were as follows: CF_4, Etch (90 percent); all other gases, Etch (98 percent); NF_3, Clean (95 percent); CF_4, Clean (80 percent), and all other gases, Clean (80 percent). There were a few exceptions where a higher DRE was assumed to ensure the calculations operated correctly when there was 100 percent abatement.

[110] If abatement information was not available for 2014 or the reported incorrectly in 2014, data from 2015 or 2016 was substituted.

the percentage of gas passing through abatement systems for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 and NF_3.

- EPA then estimated the quantity of NF_3 abated for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 (which is not abated) and NF_3. This abated quantity was then subtracted from the total abated quantity calculated as described in the bullet above.
- To account for the resulting remaining abated quantity, EPA assumed that the percentage of gas passing through abatement systems was the same across all remaining gas and process type combinations where abatement was reported for 2014.
- The percentage of gas abated was then assumed to be the same in 2011 through 2013 (if the facility claimed abatement that year) as in 2014 for each gas abated in 2014.

The revised emission factors and DREs were then applied to the estimated gas consumption for each facility by gas, process type and wafer size.[111]

For the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the F-GHGs and N_2O and estimates of manufacturing activity. The new emission factors (in units of mass of CO_2 Eq./TMLA [million square inches (MSI)]) are based on the emissions reported under EPA's GHGRP by facilities without abatement and on the TMLA estimates for these facilities based on the WFF (SEMI 2012, 2013).[112] In a refinement of the method used to estimate emissions for the non-Partner population for prior years, different emission factors were developed for different subpopulations of fabs, disaggregated by wafer size (200 mm and 300 mm). For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, SF_6 and NF_3)[113] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA), and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement.

For 2011 and 2012, estimates of TMLA relied on the capacity utilization of the fabs published by the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012). Similar to the assumption for 2007 through 2010, facilities with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. All other facilities in the United States are assumed to utilize the average percent of the manufacturing capacity without distinguishing whether fabs produce discrete products or logic products.

Non-reporting fabs were then broken out into subpopulations by wafer size (200 mm and 300 mm). using information available through the WFF. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the CO_2-equivalent emissions of that subpopulation.

---

[111] Since facilities did not report by fab before 2014, fab-wide DREs were averaged if a facility had more than one fab. For facilities that reported more than one wafer size per facility, the percentages of a facility's emissions per wafer size were estimated in 2014 and applied to earlier years, if possible. If the percentage of emissions per wafer size were unknown, a 50/50 split was used.

[112] EPA does not have information on fab-wide DREs for this time period, so it is not possible to estimate uncontrolled emissions from fabs that reported point-of-use abatement. These fabs were therefore excluded from the regression analysis. (They are still included in the national totals.)

[113] Only seven gases were aggregated because inclusion of F-GHGs that are not reported in the *Inventory* results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

Gas-specific, CO_2-equivalent emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions from which the aggregate emission factors, based on GHGRP-reported data, were developed. Estimated in this manner, the non-reporting population accounted for 4.9 and 5.0 percent of U.S. emissions in 2011 and 2012, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

2013 and 2014

For 2013 and 2014, as for 2011 and 2012, F-GHG and N_2O emissions data received through EPA's GHGRP were aggregated, by gas, across all semiconductor-manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. However, for these years WFF data was not available. Therefore, an updated methodology that does not depend on the WFF derived activity data was used to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP. For the facilities that did not report to the GHGRP (i.e., which are below EPA's GHGRP reporting threshold or are R&D facilities), emissions were estimated based on the proportion of total U.S. emissions attributed to non-reporters for 2011 and 2012. EPA used a simple averaging method by first estimating this proportion for both F-GHGs and N_2O for 2011, 2012, and 2015 and 2016, resulting in one set of proportions for F-GHGs and one set for N_2O, and then applied the average of each set to the 2013 and 2014 GHGRP reported emissions to estimate the non-reporters' emissions. Fluorinated gas-specific, CO_2-equivalent emissions for non-reporters were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions reported through EPA's GHGRP for 2013 and 2014.

GHGRP-reported emissions in 2013 were adjusted to capture changes to the default emission factors and default destruction or removal efficiencies used for GHGRP reporting, affecting the emissions trend between 2013 and 2014. EPA used the same method to make these adjustments as described above for 2011 and 2012 GHGRP data.

2015 through 2022

Similar to the methods described above for 2011 and 2012, and 2013 and 2014, EPA relied upon emissions data reported directly through the GHGRP. For 2015 through 2022, EPA took an approach similar to the one used for 2011 and 2012 to estimate emissions for the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP. However, in a change from previous years, EPA was able to develop new annual emission factors for 2015 through 2022 using TMLA from WFF and a more comprehensive set of emissions, i.e., fabs with as well as without abatement control, as new information about the use of abatement in GHGRP fabs and fab-wide were available. Fab-wide DREs represent total fab CO_2 Eq.-weighted controlled F-GHG and N_2O emissions (emissions after the use of abatement) divided by total fab CO_2 Eq.-weighted uncontrolled F-GHG and N_2O emissions (emission prior to the use of abatement).

Using information about reported emissions and the use of abatement and fab-wide DREs, EPA was able to calculate uncontrolled emissions (each total F-GHG and N_2O) for every GHGRP reporting fab. Using this, coupled with TMLA estimated using methods described above (see 2011 through 2012), EPA derived emission factors by year, gas type (F-GHG or N_2O), and wafer size (200 mm and less or 300 mm) by dividing the total annual emissions reported by GHGRP reporters by the total TMLA estimated for those reporters. These emission factors were multiplied by estimates of non-reporter TMLA to arrive at estimates of total F-GHG and N_2O emissions for non-reporters for each year. For each wafer size, the total F-GHG emissions were disaggregated into individual gases using the shares of total emissions represented by those gases in the emissions reported to the GHGRP by unabated fabs producing that wafer size.

Data Sources

GHGRP reporters, which consist of former EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2c Method in the *2019 Refinement to the 2006 IPCC Guidelines*, this method uses different emission and byproduct generation factors for different F-GHGs and process types and uses factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes

(in situ thermal, in situ plasma, and remote plasma). Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions. For the years 2011 through 2013 reported emissions, semiconductor manufacturers used older emission factors to estimate their F-GHG emissions (Federal Register / Vol. 75, No. 230 /December 1, 2010, 74829). Subpart I emission factors were updated for 2014 by EPA as a result of a larger set of emission factor data becoming available as part of the Subpart I petition process, which took place from 2011 through 2013. In addition to semiconductor manufacturing, GHGRP also includes reported emissions from MEMS and PV producers.

Historically, semiconductor industry partners estimated and reported their emissions using a range of methods and uneven documentation. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Partners are estimated to have accounted for between 56 and 79 percent of F-GHG emissions from U.S. semiconductor manufacturing between 1995 and 2010, with the percentage declining in recent years as Partners increasingly implemented abatement measures.

Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2012, 2013, 2016, 2018, 2021, and 2023) (e.g., Semiconductor Materials and Equipment Industry 2021). Actual worldwide capacity utilizations for 2008 through 2010 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA 2009 through 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001; ITRS 2007; ITRS 2008; ITRS 2011; ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI. Actual quarterly U.S. capacity utilizations for 2011, 2012, 2014 to 2022 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022).

Estimates of PV manufacturing capacity, which are used to calculate emissions from non-reporting facilities, are based on data from two sources. A historical market analysis from DisplaySearch provided estimates of U.S. manufacturing capacity from 2000 to 2009 (DisplaySearch 2010). Domestic PV cell production for 2012 was obtained from a Congressional Research Service report titled *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support* (Platzer 2015).

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from the electronics industry, represented in equation form as:

Equation 4-20: Total Emissions from Electronics Industry

$$\begin{aligned}\text{Total Emissions } (\mathrm{E}_T) &= \text{Semiconductors F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{Semi}) \\ &+ \text{MEMS F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{MEMS}) + \text{PV F-GHG and } \mathrm{N_2O} \text{ Emissions } (\mathrm{E}_{PV}) \\ &+ \text{HFC, PFC and } \mathrm{SF_6} \text{ F-HTFs Emissions } (\mathrm{E}_{HTF})\end{aligned}$$

The uncertainty in the total emissions for the electronics industry, presented in Table 4-124 below, results from the convolution of four distributions of emissions, namely from semiconductors manufacturing, MEMS manufacturing, PV manufacturing and emissions of heat transfer fluids. The approaches for estimating uncertainty in each of the sources are described below:

Semiconductors Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from semiconductor manufacturing, represented in equation form as:

Equation 4-21: Total Emissions from Semiconductor Manufacturing

$$\begin{aligned}\text{Semiconductors F-GHG and } N_2O \text{ Emissions } (E_{Semi}) \\ = \text{ GHGRP Reported F-GHG Emissions } (ER,\text{F-GHG, Semi}) \\ + \text{ Non-Reporters' Estimated F-GHG Emissions } \left(E_{NR,\text{F-GHG},Semi}\right) \\ + \text{ GHGRP Reported } N_2O \text{ Emissions } \left(E_{R,N_2O,Semi}\right) \\ + \text{ Non-Reporters' Estimated } N_2O \text{ Emissions } \left(E_{NR,N_2O,Semi}\right)\end{aligned}$$

The uncertainty in E_{Semi} results from the convolution of four distributions of emissions, $E_{R,F\text{-}GHG,Semi}$ $E_{R,N2O,Semi}$ $E_{NR,F\text{-}GHG,Semi}$ and $E_{NR,N2O,Semi}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for E_{Semi} are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG,Semi}$, or GHGRP-reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm or less wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment are based on an uncertainty analysis conducted during the assessment of emission estimation methods for the Subpart I rulemaking in 2012 (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028).[114] This assessment relied on facility-specific gas information by gas and wafer size, and incorporated uncertainty associated with both emission factors and gas consumption quantities. The 2012 analysis did not consider the use of abatement.

For the industry segment that manufactured 200 mm wafers, estimates of uncertainty at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of uncertainty at the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. For gases for which uncertainty was not analyzed in the 2012 assessment (e.g., CH_2F_2), EPA applied the 95 percent CI range equivalent to the range for the gas and industry segment with the highest uncertainty from the 2012 assessment. These gas and wafer-specific uncertainty estimates were developed to represent uncertainty at a facility-level, but they are applied to the total emissions across all the facilities that did not abate emissions as reported under EPA's GHGRP at a national-level. Hence, it is noted that the uncertainty estimates used may be overestimating the uncertainties at a national-level.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of all gases from all cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of zero percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3, and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent

[114] On November 13, 2013, EPA published a final rule revising Subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the Subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

of the gases are abated (i.e., the maximum value) and that 50 percent is the most likely value, and the minimum is zero percent. Consideration of abatement then resulted in four additional industry segments, two 200-mm wafer-processing segments (one fully and one partially abating each gas) and two 300-mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Monte Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG,Semi}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP-reporting facilities ($E_{R,F\text{-}GHG,Semi}$).

The uncertainty in $E_{R,N2O,Semi}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for Subpart I (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of zero percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the Subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI 2009). The inputs were used to simulate emissions for each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each facilities' reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,\ F\text{-}GHG,Semi}$ and $E_{NR,\ N2O,Semi}$ entailed developing estimates of uncertainties for the emissions factors and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. The most probable utilization is assumed to be 82 percent, with the highest and lowest utilization assumed to be 89 percent, and 70 percent, respectively. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases (MT units) and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities. For each wafer size for reporting facilities, emissions of individual gases were regressed on TMLA (with an intercept forced to zero) for 10,000 emission and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5^{th} and the 97.5^{th} percentile of these emission factors are determined, and the bounds are assigned as the percent difference from the estimated emission factor.

The next step in estimating the uncertainty in emissions of reporting and non-reporting facilities in semiconductor

manufacture is convolving the distribution of reported emissions, emission factors, and TMLA using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported F-GHG gas- and wafer size-specific emissions are assumed to be normally distributed, and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The were some instances, though, where departures from normality were observed for variables, including for the distributions of the gas- and wafer size-specific N_2O emissions, TMLA, and non-reporter emission factors, both for F-GHGs and N_2O. As a result, the distributions for these parameters were assumed to follow a PERT beta distribution.

MEMS Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from MEMS manufacturing, represented in equation form as:

Equation 4-22: Total Emissions from MEMS Manufacturing

$$\text{MEMS F-GHG and } N_2O \text{ Emissions } (E_{MEMS}) = \text{GHGRP Reported F-GHG Emissions } (E_{R,\text{F-GHG},MEMS}) + \text{GHGRP Reported } N_2O \text{ Emissions } (E_{R,N2O,\,MEMS})$$

$$\text{MEMS F-GHG and } N_2O \text{ Emissions } (E_{MEMS}) = \text{GHGRP Reported F-GHG Emissions } \left(E_{R,\,\text{F-GHG},MEMS}\right) + \text{GHGRP Reported } N_2O \text{ Emissions } \left(E_{R,N_2O,MEMS}\right)$$

Emissions from MEMS manufacturing are only quantified for GHGRP reporters. MEMS manufacturers that report to the GHGRP all report the use of 200 mm wafers. Some MEMS manufacturers report using abatement equipment. Therefore, the estimates of uncertainty at the 95 percent CI for each gas emitted by MEMS manufacturers are set equal to the gas-specific uncertainties for manufacture of 200mm semiconductor wafers with partial abatement. The same assumption is applied for uncertainty levels for GHGRP reported MEMS N_2O emissions ($E_{R,N2O,MEMS}$).

PV Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from PV manufacturing, represented in equation form as:

Equation 4-23: Total Emissions from PV Manufacturing

$$\text{PV F-GHG and } N_2O \text{ Emissions } (E_{PV}) = \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,\text{F-GHG},PV}) + \text{Non-Reporters' Estimated } N_2O \text{ Emissions } (E_{NR,N2O,PV})$$

$$\text{PV F-GHG and } N_2O \text{ Emissions } (E_{PV}) = \text{Non-Reporters' Estimated F-GHG Emissions } \left(E_{NR,\text{F-GHG},PV}\right) + \text{Non-Reporters' Estimated N2O Emissions } \left(E_{NR,N_2O,PV}\right)$$

Emissions from PV manufacturing are only estimated for non-GHGRP reporters in 2022. There were no reported emissions from PV manufacturing in GHGRP in 2022. The "Non-Reporters' Estimated F-GHG Emissions" term in Equation 4-23 was estimated using an emission factor developed using emissions from reported data in 2015 and 2016 and total non-reporters' capacity. Due to a lack of information and data and because they represent similar physical and chemical processes, the uncertainty at the 95 percent CI level for non-reporter PV capacity is assumed to be the same as the uncertainty in non-reporter TMLA for semiconductor manufacturing. Similarly, the uncertainty for the PV manufacture emission factors are assumed to be the same as the uncertainties in emission factors used for non-reporters in semiconductor manufacture.

Heat Transfer Fluids Emission Uncertainty

There is a lack of data related to the uncertainty of emission estimates of heat transfer fluids used for electronics manufacture. Therefore, per the *2006 IPCC Guidelines* (IPCC 2006, Volume 3, Chapter 6), uncertainty bounds of 20

percent were applied to estimate uncertainty associated with the various types of heat transfer fluids, including PFCs, HFC, and SF_6, at the national level.

The results of the Approach 2 quantitative uncertainty analysis for electronics manufacturing are summarized in Table 4-124. These results were obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility that manufactures semiconductors, MEMS, or PVs and use heat transfer fluids. The emissions estimate for total U.S. F-GHG, N_2O, and HTF emissions from electronics manufacturing were estimated to be between 4.44 and 5.02 MMT CO_2 Eq. at a 95 percent CI level. This range represents 6 percent below to 6 percent above the 2022 emission estimate of 4.73 MMT CO_2 Eq. for all emissions from electronics manufacture. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-124: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Electronics Manufacture (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Electronics Industry	HFC, PFC, SF_6, NF_3, and N_2O	4.7	4.4	5.0	-6%	+6%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For its GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[115] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

Any resubmitted emissions data reported to EPA's GHGRP from all prior years were updated in this *Inventory*. Additionally, EPA made the following changes:

- To estimate non-reporter F-GHG and N_2O emissions, EPA relies on data reported through Subpart I and the World Fab Forecast. This process requires EPA to map facilities that report through Subpart I and which are also represented in the World Fab Forecast. For this *Inventory* update, EPA identified and made

[115] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

corrections to a few instances of this mapping based on new information and additional reviews of the data. This had minimal effects on emission estimates.

- EPA re-ran regression analyses for years 2010 to 2021 to reflect updates to Subpart I and the World Fab Forecast. These changes had minor effects on the emission factors, standard error, and R^2 values for all years. This resulted in the recalculation of non-reporter's F-GHG and N_2O estimates for all years.
- EPA recalculated HTF emissions for years 1990 to 2021 using IPCC *Fifth Assessment Report* (AR5) GWP values (IPCC 2013). Emission estimates were incorrectly calculated using the IPCC *Fourth Assessment Report* (AR4) GWP values (IPCC 2007) in the previous *Inventory* (EPA 2023). Overall, the impact of these recalculations led to an average decrease of 0.009 MMT CO_2 Eq. (0.19 percent) across the time series (1990 through 2021).
- EPA recalculated fluorinated GHG consumption for 2014 to 2021 using the following methodology. Fluorinated GHG consumption estimates for unabated fabs were calculated using reported GHGRP emissions data and default emission factors for Subpart I. Because certain fluorinated GHGs are generated as by-products as well as used as input gases, both input gas emission factors and by-product gas emission factors were factored into this calculation. For abated fabs, a "consumption factor" was developed by dividing the reported emissions of each fluorinated GHG from unabated fabs by the estimated consumption of each fluorinated GHG for each wafer size. Fluorinated GHG consumption for 2021 was estimated based on GDP growth of the 2020 consumption estimate. The consumption estimate will be updated with reported 2021 GHGRP emissions data.
- EPA refined the non-reporting population for 2015 to 2022 by conducting an analysis into the criteria being used to determine which fabs should be included and excluded from this population. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.02 MMT CO_2 Eq. (0.45 percent) for the time series 2015 to 2022.
- EPA recalculated non-reporter emissions for 2015 to 2022 by developing emission factors for individual gases and calculated on an MT basis. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.04 MMT CO_2 Eq. (0.84 percent) for the time series 2014 to 2022.

Planned Improvements

The *Inventory* methodology uses data reported through the EPA Partnership (for earlier years) and EPA's GHGRP (for later years) to extrapolate the emissions of the non-reporting population. While these techniques are well developed, the accuracy of the emissions estimates for the non-reporting population could be further increased through EPA's further investigation of and improvement upon the accuracy of estimated activity in the form of TMLA.

The *Inventory* uses utilization from two different sources for various time periods–SEMI to develop PEVM and to estimate non-Partner emissions for the period 1995 to 2010 and U.S. Census Bureau for 2011 through 2022. SEMI reported global capacity utilization for manufacturers through 2011. U.S. Census Bureau capacity utilization include U.S. semiconductor manufacturers as well as assemblers. Further analysis on the impacts of using a new and different source of utilization data could prove to be useful in better understanding of industry trends and impacts of utilization data sources on historical emission estimates.

Estimates of semiconductor non-reporter and non-Partner emissions are based on EPA-developed emission factors for the time periods pre-2010, 2011 through 2012, and 2015 through 2022. Based on the data available for these time periods, the methods used to develop emission factors for non-reporters and non-Partners are slightly inconsistent for semiconductors (e.g., how data representing emissions and TMLA from the manufacture of various wafer sizes are aggregated or disaggregated for purposes of calculating emission factors). Further analyses to support potentially adjusting the methods for developing these emission factors could be done to better ensure consistency across the time series.

The methodology for estimating semiconductor emissions from non-reporters uses data from the International Technology Roadmap for Semiconductors (ITRS) on the number of layers associated with various technology node sizes. The ITRS has now been replaced by the International Roadmap for Devices and Systems (IRDS), which has published updated data on the number of layers used in each device type and node size (in nanometers). Incorporating this updated dataset will improve the accuracy of emissions estimates from non-reporting semiconductor fabs.

4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F)

This reporting category (2F) includes emissions from the substitution of ozone-depleting substance (ODS). Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and carbon dioxide (CO_2) are used as alternatives to several classes of ODS that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[116] Ozone-depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and directs EPA to address HFCs by phasing down production and consumption (i.e., production plus import minus export), maximizing reclamation and minimizing releases from equipment, and facilitating the transition to next-generation technologies through sector-based restrictions. Emission estimates for HFCs, PFCs, and CO_2 used as substitutes for ODSs are provided in Table 4-125 and Table 4-126.[117]

Table 4-125: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	6.1	6.9	7.8	9.4	10.5
HFC-125	+	8.2	48.8	53.1	57.8	66.3	72.0
HFC-134a	+	72.8	56.4	55.3	54.1	50.0	48.3
HFC-143a	+	10.0	29.7	29.9	29.9	30.0	29.8
HFC-236fa	0.0	1.0	0.8	0.7	0.7	0.6	0.6
CF_4	0.0	+	+	+	+	+	0.1
CO_2	+	+	+	+	+	+	+
Other Saturated HFCs[a]	0.3	6.9	15.9	16.0	15.9	16.3	16.8
Other PFCs and HFOs[b]	+	0.1	+	+	+	+	+
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.

[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse

[116] [42 U.S.C § 7671, CAA Title VI].

[117] Emissions of ODS are not included here consistent with UNFCCC reporting guidelines for national inventories noted in Box 4-1. See Annex 6.2 for more details on emissions of ODS. Emissions from CO_2 used in the food and beverage industry are separately reported in Chapter 4.16 Carbon Dioxide Consumption but does not include CO_2 in ODS substitute use sectors as a refrigerant, foam blowing agent, or fire extinguishing agent.

collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.
Note: Totals may not sum due to independent rounding.

Table 4-126: Emissions of HFCs, PFCs, and CO_2 from ODS Substitution (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0	1	2	2	2	2	3
HFC-32	0	397	9,008	10,156	11,461	13,958	15,582
HFC-125	+	2,580	15,406	16,761	18,240	20,909	22,704
HFC-134a	+	56,029	43,419	42,558	41,590	38,447	37,167
HFC-143a	+	2,093	6,188	6,230	6,234	6,240	6,203
HFC-236fa	0	127	99	91	84	78	72
CF_4	0	3	5	5	4	4	4
CO_2	14	1,325	3,093	3,303	3,516	3,734	3,969
Other Saturated HFCs[a]	M	M	M	M	M	M	M
Other PFCs and HFOs[b]	M	M	M	M	M	M	M

+ Does not exceed 0.5 MT.
M (Mixture of Gases).
[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.
[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[118] In 1993, the use of HFCs in foam production began, and in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased out. In 1995, these compounds also found applications as solvents. Non-fluorinated ODS substitutes, such as CO_2, have been used in place of ODS in certain foam production and fire extinguishing uses since the 1990s.

The use and subsequent emissions of HFCs, PFCs, and CO_2 as ODS substitutes has been increasing from small amounts in 1990 to 178.1 MMT CO_2 Eq. emitted in 2022. This increase was in large part the result of efforts to phase out CFCs, HCFCs, and other ODSs in the United States. Use and emissions of HFCs are expected to start decreasing in the next few years and continue downward as production and consumption of HFCs are phased down to 15 percent of their baseline levels by 2036 through an allowance allocation and trading program established by EPA. Improvements in recovery practices and the use of alternative gases and technologies, through voluntary actions and in response to existing and potential future regulations under the AIM Act, will also contribute to a reduction in HFC use and emissions.

Table 4-127 presents emissions of HFCs, PFCs, and CO_2 as ODS substitutes by end-use sector for 1990 through 2022. The refrigeration and air-conditioning sector is further broken down by sub-sector. The end-use sectors that contributed the most toward emissions of HFCs, PFCs, and CO_2 as ODS substitutes in 2022 include refrigeration and air-conditioning (144.6 MMT CO_2 Eq., or approximately 81 percent), aerosols (17.0 MMT CO_2 Eq., or approximately 10 percent), and foams (11.7 MMT CO_2 Eq., or approximately 7 percent). Within the refrigeration and air-conditioning end-use sector residential unitary AC, part of the Residential Stationary Air-conditioning subsector

[118] R-404A contains HFC-125, HFC-143a, and HFC-134a.

shown below, was the highest emitting end-use (40.8 MMT CO_2 Eq.), followed by large retail food, which is part of the Commercial Refrigeration subsector. Each of the end-use sectors is described in more detail below.

Table 4-127: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990	2005	2018	2019	2020	2021	2022
Refrigeration/Air Conditioning	**+**	**83.0**	**122.7**	**126.5**	**130.6**	**139.5**	**144.6**
Commercial Refrigeration	+	14.9	39.6	40.2	40.6	41.0	41.4
Domestic Refrigeration	+	0.2	1.2	1.2	1.2	1.1	1.0
Industrial Process Refrigeration	+	1.8	13.8	15.0	16.2	17.4	18.6
Transport Refrigeration	+	1.6	6.9	7.4	7.9	8.4	8.8
Mobile Air Conditioning	+	61.5	28.7	26.6	24.6	22.9	20.8
Residential Stationary Air Conditioning	+	1.2	26.2	29.4	33.2	41.5	46.4
Commercial Stationary Air Conditioning	+	1.7	6.2	6.6	6.9	7.3	7.6
Aerosols	**0.2**	**10.2**	**16.7**	**17.0**	**17.3**	**17.7**	**17.0**
Foams	**+**	**3.5**	**14.2**	**14.1**	**13.7**	**10.8**	**11.7**
Solvents	**+**	**1.6**	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**
Fire Protection	**+**	**1.2**	**2.4**	**2.5**	**2.5**	**2.6**	**2.6**
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, metallurgical, and other industries). As the ODS phaseout has taken effect, most equipment has been retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[119] R-404A, and R-507A.[120] Lower-GWP options such as hydrofluoroolefin (HFO)-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) and HFC/HFO blends in retail food refrigeration, are also being used. Manufacturers of residential and commercial air conditioning have announced their plans to use HFC-32 and R-454B[121] in the future, and at least one manufacturer has announced the availability of chillers operating on HFC-32 as of 2023 (Carrier, 2023). These refrigerants are emitted to the atmosphere during equipment operation (as a result of component failure, leaks, and purges), as well as at manufacturing (if charged at the factory), installation, servicing, and disposal events.

[119] R-410A contains HFC-32 and HFC-125.

[120] R-507A, also called R-507, contains HFC-125 and HFC-143a.

[121] R-454B contains HFC-32 and HFO-1234yf.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry is using HFC-227ea as well. Conversely, since the use of CFC propellants in other types of aerosols was banned in the Unites States in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODSs in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

Chlorofluorocarbons and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds into alternatives such as CO_2 and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce PU appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a, and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and HCFO-1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

Chlorofluorocarbons, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of these solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as

a low-GWP option and 2-BTP is being use in niche applications. As fire protection equipment is tested or deployed, emissions of these fire protection agents occur.

Methodology and Time-Series Consistency

Using a Tier 2 method in accordance with the IPCC methodological decision tree, a detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs, PFCs, and CO_2. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for 80 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions across the 80 end-uses in the Vintaging Model. In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock (e.g., number of air conditioning units in operation) for the current year or ODS consumption before transition to alternatives began (e.g., in 1985 for most end-uses). Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed.

Inputs to the ODS substitutes uncertainty model generally take on a normal distribution with a 90 to 95 percent confidence interval but do utilize other probability density functions such as a uniform or PERT BETA distribution. The uncertainty inputs are based on conversations with industry experts and how certain assumptions are developed in the Vintaging Model. For example, if the Vintaging Model estimates are specifically aligned with actual reported data, then the uncertainty is decreased. This can be seen with the unitary AC end-use where annual stock data is aligned with sales data published by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). The stock is assumed to be fairly accurate and therefore, uncertainty range for the stock of unitary AC is set to an upper and lower bound of only 2.5 percent. The most significant sources of uncertainty for the substitution of ODS source category include the total stock of refrigerant installed in industrial process refrigeration and cold storage equipment, as well as the charge size for technical aerosols using HFC-134a. For technical aerosols, a triangular distribution is utilized to apply an asymmetrical range to the inventory value. This is to account for the

uncertainty that technical aerosols using HFC-134a might have higher market penetration than what the Vintaging Model currently estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-128. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 170.8 and 205.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4.1 percent below to 15.1 percent above the emission estimate of 178.1 MMT CO_2 Eq.

Table 4-128: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	178.1	170.8	205.1	-4.1%	+15.1%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter. Category specific QA/QC findings are described below.

The QA and verification process for individual gases and sources in the Vintaging Model includes review against up-to-date market information, including equipment stock estimates, leak rates, and sector transitions to new chemicals and technologies. In addition, comparisons against published emission and consumption sources by gas and by source are performed when available as described further below. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates. For the purposes of reporting emissions to protect Confidential Business Information (CBI), some HFCs and PFCs are grouped into two unspecified mixes of saturated HFCs and other PFCs and HFOs. The HFCs and PFCs within the unspecified mix of HFCs and PFCs are modelled and verified individually in the same process as all other gases and sources in the Vintaging Model.

Data from EPA's Greenhouse Gas Reporting Program (GHGRP)[122] and emissions of some fluorinated greenhouse gases estimated for the contiguous United States by scientists at the National Oceanic and Atmospheric Administration (NOAA) were used to perform additional quality control as specified in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019)*. These comparisons are detailed further in Annex 3.9.

Recalculations Discussion

For the current *Inventory*, updates to the Vintaging Model included updating 2022 growth rates for residential and commercial unitary air-conditioning to align with annual sales estimates published by AHRI. Projected growth rates

[122] For the GHGRP data, EPA verifies annual facility-level and company-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data.

were updated for residential unitary air-conditioning to align with projected residential housing available from the Energy Information Administration (EIA) and commercial unitary air-conditioning growth rates were updated based on new commercial floorspace growth projections from EIA (EPA 2023a). Growth rates for window units were updated to align with sales data for Energy Star- and non-Energy Star-certified units (EPA 2023b).

The Vintaging Model was also updated to include the addition of two end-uses representing multi-split air-conditioning units: small ductless mini-split and multi-split air-conditioning and large ductless mini-split and multi-split air-conditioning. These end-uses were split from the existing residential unitary air-conditioning end-use. Stock for ductless mini-split and multi-split air-conditioning systems were estimated based on the EIA Residential Energy and Consumption Survey (RECS) and growth projected based on annual sales of split systems under 33,000 BTU/h (small mini/multi-splits) and split systems between 33,000 BTU/h and 65,000 BTU/h (large mini/multi-splits) published by AHRI (EPA 2023c).

In addition, the market size and growth rates of the streaming agents end-use in the Fire Suppression sector was updated, improving alignment of halon 1211 consumption with the 2022 Fire Suppression Technical Options Committee (FSTOC) estimates, the lifetime was adjusted to reflect internal inspection timelines, rather than physical extinguisher lifetimes, and refilling of leaks throughout the lifetime of extinguishers was modeled (EPA 2023d).

Together, these updates increased ODS substitute emissions on average by 0.06 MMT CO_2 Eq. (0.6 percent) between 1990 and 2021, compared to the previous (i.e., 2023) *Inventory* submission.

Planned Improvements

Future improvements to the Vintaging Model are planned for the Refrigeration and Air-conditioning, Fire Suppression, and Aerosols sectors. Specifically, refrigerated storage space estimates published biannually from the United States Department of Agriculture (USDA) are being compared to cold storage warehouse space currently estimated in the Vintaging Model. Flooding agent fire suppression market transitions are under review to align more closely with real world activities. In addition, further refinement of HFC consumption in MDIs is expected from review of data collected on HFC use for MDI production, imports, and exports in response to requests pursuant to AIM Act regulations for application-specific allowances for MDIs. EPA expects these revisions to be prepared for the 2025 *Inventory* submission.

As discussed above, future reporting under the AIM Act may provide useful information for verification purposes and possible improvements to the Vintaging Model, such as information on HFC stockpiling behaviors. EPA expects this reporting by late 2023 and incorporation into the 2025 or 2026 report. Should the data suggest structural changes to the model, such as the handling of stockpiles before use, EPA expects to introduce the revised model for the 2025 or 2026 *Inventory* submission.

Several potential improvements to the *Inventory* were identified in the 2022 *Inventory* submission based on the comparisons mentioned above and discussed in Annex 3.9—net supply values from the GHGRP and emission estimates derived from atmospheric measurements—and remain valid. To estimate HFC emissions for just the contiguous United States, matching the coverage by the atmospheric measurements, EPA will investigate the availability of data from Alaska, Hawaii, and U.S. territories. This is planned by the next (i.e., 2025) *Inventory* submission. To improve estimates of HFC-125 and HFC-143a, further research into the refrigeration market can be made. Research in this industry on the shift away from blends such as R-404A or success in lowering emission rates could be used to improve the *Inventory* estimate. This is planned for the 2025 *Inventory*. That said, for the years where both the atmospheric measurements and the model display a roughly constant emission of HFC-143a at similar levels, the new results suggest robust estimates for the refrigeration market. Uncertainty estimates by species would aid in comparisons to atmospheric data. EPA continues to explore the possibility of revising the Monte Carlo analysis to differentiate between species, starting with the higher-emitted HFCs identified above, in a future (i.e., 2025) *Inventory* submission. Reclamation reports and, when available, information gathered under the AIM Act, could be used to improve the understanding of how chemical moves through the economy and could resolve some of the temporal effects discussed in Annex 3.9. This would likely require revisions to the basic model

structure and could be introduced for the 2026 or 2027 *Inventory* submission. The additional data from the atmospheric measurements suggests additional items to investigate. The faster uptick in HFC-32 and HFC-125 emissions suggests additional emissions of R-410A compared to the model's estimation. Further investigation into the average emission rate, the variability over time of the emission rate, stocks, lifetimes, and other factors will be investigated for the next (i.e., 2025) *Inventory* submission.

4.26 Electrical Equipment (CRT Source Category 2G1)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas. Another greenhouse gas emitted in much smaller amounts by the electric power industry is tetrafluoromethane (CF_4), which is mixed with SF_6 to avoid liquefaction at low temperatures (Middleton 2000). While mixed gas circuit breakers are more common in extremely cold climates in geographies outside of the United States, some U.S. manufacturers of electrical equipment are emitting CF_4 during the manufacturing of equipment designed to hold the SF_6/CF_4 gas mixture. However, no electrical equipment facilities in the United States have reported emissions of or equipment using CF_4. SF_6 emissions exceed PFC emissions from electric power systems on both a GWP-unweighted and GWP-weighted basis. This reporting category (2G1) includes emissions from electrical equipment.

Fugitive emissions of SF_6 and CF_4 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 and CF_4 from equipment manufacturing and from electrical equipment systems were estimated to be 5.1 MMT CO_2 Eq. (0.3 kt) in 2022. This quantity represents a 79 percent decrease from the estimate for 1990 (see Table 4-129 and Table 4-130). There are a few potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's GHGRP, regulatory drivers at the state and local levels, and research and development of alternative gases to SF_6 that can be used in gas-insulated substations. Utilities participating in the Partnership have lowered their emission factor from 13 percent in 1999 (kg SF_6 emitted per kg of nameplate capacity) to 0.9 percent in 2022. SF_6 emissions reported by electric power systems to EPA's GHGRP have decreased by 56 percent from 2011 to 2022,[123] with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program

[123] Analysis of emission trends from facilities reporting to EPA's GHGRP is imperfect due to an inconsistent group of reporters year to year. A facility that has reported total non-biogenic greenhouse gas emissions below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years to EPA's GHGRP can discontinue reporting for all direct emitter subparts. For this sector, most of the variability in the group of reporters is due to facilities exiting the GHGRP due to being below one of these thresholds; however, facilities must re-enter the program if their emissions at a later date are above 25,000 MT CO_2 Eq., which may occur for a variety of reasons, including changes in facility size and changes in emission rates.

(Ottinger et al. 2014). Total emissions from electrical equipment in 2022 were lower than 2021 emissions, decreasing by 15.3 percent.

Table 4-129: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Electric Power Systems	24.3	11.2	4.7	5.7	5.3	5.6	4.8
Electrical Equipment Manufacturers	0.3	0.7	0.3	0.4	0.5	0.4	0.3
Total	24.7	11.9	5.0	6.1	5.9	6.0	5.1

Note: Totals may not sum due to independent rounding.

Table 4-130: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

	1990	2005	2018	2019	2020	2021	2022
SF_6 Emissions	1.0	0.5	0.2	0.3	0.3	0.3	0.2
CF_4 Emissions	+	+	NO	+	+	+	+

+ Does not exceed 0.5 kt.
NO (Not Occurring)

Methodology and Time-Series Consistency

The estimates of emissions from electrical equipment are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in 1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 through 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales was used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines*.[124] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

[124] Ideally, sales to utilities in the United States between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

Equation 4-24: Estimation for SF_6 Emissions from Electric Power Systems

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [125]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2022 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2022 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); (3) SF_6 emissions from California estimated by the California Air Resources Board (CARB) and (4) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, 2013, and 2016 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013, and 2017), and 2019, 2020, and 2021 Homeland Infrastructure Foundation-Level Data (HIFLD) (HIFLD 2019, 2020, and 2021), which was applied to the electric power systems that do not report to EPA (Non-Reporters). Total U.S. transmission mileage was interpolated between 2016 and 2019 to estimate transmission mileage of electric power systems in 2017 and 2018. (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

[125] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

Partners

Over the period from 1999 to 2022, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership,[126] represented 49 percent, on average, of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2022, less than 1 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 99.6 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP.[127] Overall, the emission rates reported by Partners have decreased significantly throughout the time series.

Non-Partners

Non-Partners consist of two groups: Utilities that have reported to the GHGRP beginning in 2012 (reporting 2011 emissions) or later years (GHGRP-only Reporters) and utilities that have never reported to the GHGRP (Non-Reporters). EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under the Partnership). As under the Partnership, electric power systems that report their SF_6 emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. GHGRP-Only Reporters accounted for 16 percent of U.S. transmission miles and 14 percent of estimated U.S. emissions from electric power system in 2022.[128]

From 1999 through 2018, emissions from both GHGRP-only Reporters and Non-Reporters were estimated in the same way. From 1999 through 2008, emissions were estimated using the results of a regression analysis that correlated the 1999 emissions from Partner utilities with their 1999 transmission miles.[129] The 1999 regression coefficient (emission factor) was held constant through 2008 and multiplied by the transmission miles estimated for the non-Partners for each year.

The 1999 regression equation for Non-Partners was developed based on the emissions reported by a subset of Partner utilities who reported non-zero emissions and non-zero transmission miles (representing approximately 50 percent of total U.S. transmission miles). The regression equation for 1999 is displayed in the equation below.

---

[126] Starting in the 1990 to 2015 *Inventory*, partners who had reported three years or less of data prior to 2006 were removed. Most of these Partners had been removed from the list of current Partners but remained in the Inventory due to the extrapolation methodology for non-reporting partners.

[127] Only data reported as of August 21, 2023 are used in the emission estimates for the prior year of reporting. Emissions for Partners that did not report to the Partnership or GHGRP are extrapolated for three years using a utility-specific transmission mile growth rate. After four consecutive years of non-reporting they are included in the 'non-reporting Partners' category. It should be noted that data reported through EPA's GHGRP must go through a verification process. For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted.

[128] GHGRP-reported and Partner transmission miles from a number of facilities were equal to zero with non-zero emissions. These facilities emissions were added to the emissions totals for their respective parent companies when identifiable and not included in the regression equation when not identifiable or applicable. Other facilities reported non-zero transmission miles with zero emissions, or zero transmission miles and zero emissions. These facilities were not included in the development of the regression equations (discussed further below). These emissions are already implicitly accounted for in the relationship between transmission miles and emissions.

[129] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

Equation 4-25: Regression Equation for Estimating SF_6 Emissions of Non-Reporting Facilities in 1999

$$\text{Emissions (kg)} = 0.771 \times \text{Transmission Miles}$$

The 1999 emission factor (0.77 SF_6 emissions/Transmission Miles) for the non-Partners was held constant to estimate non-Partner emissions from 2000-2008. Non-partner emissions were assumed to decrease beginning in 2009, trending toward the regression coefficient (emission factor) calculated for the GHGRP-only reporters based on their reported 2011 emissions and transmission miles. Emission factors for 2009 and 2010 were linearly interpolated between the 1999 and 2011 emission factors. For 2009, the emissions of non-Partners were estimated by multiplying their transmission miles by the interpolated 2009 emission factor (0.65 kg/transmission mile).

The 2011 regression equation was developed based on the emissions reported by GHGRP-Only Reporters who reported non-zero emissions and non-zero transmission miles (representing approximately 23 percent of total U.S. transmission miles). The regression equation for 2011 is displayed below.

Equation 4-26: Regression Equation for Estimating SF_6 Emissions of GHGRP-Only Reporters in 2011

$$\text{Emissions (kg)} = 0.397 \times \text{Transmission Miles}$$

For 2011 and later years, the emissions of GHGRP-only reporters were generally equated to their reported emissions, unless they did not report. The emissions of GHGRP-only reporters that have years of non-reporting between reporting years are gap filled by interpolating between reported values.

For 2010 and later years, the emissions of non-Reporters were estimated by multiplying their transmission miles by the estimated 2010 emission factor (0.52 kg/transmission mile), which was held constant from 2010 through 2022.

Off-ramping GHGRP Facilities

The GHGRP program has an "off-ramp" provision (40 CFR Part 98.2(i)) that exempts facilities from reporting under certain conditions. If reported total greenhouse gas emissions are below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years, the facility may elect to discontinue reporting. Emissions of GHGRP reporters that have off-ramped are extrapolated for three years of non-reporting using a utility-specific transmission mile growth rate, unless the utility has transmission mileage in California. After three consecutive years of non-reporting, emissions for facilities (except those in California) that off-ramped from GHGRP were estimated using an emissions rate derived from the reported emissions and transmission miles of GHGRP-only reporters in the respective year. For facilities in California, a California-specific emissions rate is used as described in the following section.

Table 4-131: GHGRP-only Average Emission Rate (kg per mile)

Year	2011	2018	2019	2020	2021	2022
Average emission rate	0.43	0.22	0.29	0.27	0.25	0.22

Table 4-132: Categorization of Utilities and Timeseries for Application of Corresponding Emission Estimation Methodologies

Categorization of Utilities	Timeseries
Partners	1999 - 2021
Non-Partners (GHGRP-Only)	2011 – 2021
Non-Partners (Remaining Non-Reporting Utilities)	1999 – 2021
Off-ramping GHGRP Facilities	2017 – 2021

California

CARB reports the total SF_6 emissions from electrical equipment within the state of California (CARB 2023). Because California utilities are required to report their SF_6 emissions to CARB even when they are not required to report to the GHGRP, CARB's estimates of California SF_6 emissions are expected to be more accurate for the California utilities that do not report to GHGRP than the methodology described above. As a result, the CARB SF_6 emissions estimates are used as California's contribution to the national total for 2011-2022, except in years where CARB's estimate is smaller than the California estimates reported to EPA or years for which CARB has not published estimates. Since CARB's emissions estimates include emissions from facilities that do not report to GHGRP, emissions for California GHGRP reporters that have off-ramped are not extrapolated. Specifically, CARB estimates are used for 2011, 2012, 2013, 2014, 2017, 2018, 2019, 2020, and 2021.

For each utility with transmission mileage in California, the GHGRP or voluntarily reported emissions attributed to California for that utility were determined using the percentage of that utility's transmission mileage within California based on data from HIFLD. These emissions across all California utilities were summed to find the California emissions that were reported through GHGRP or voluntarily to the EPA. Then, if CARB's emissions estimates for the reporting year were larger than the those from GHGRP and voluntary reporting, CARB's emissions replaced the California emissions from GHGRP and voluntary reporting.

If CARB's emissions estimates were lower than the California emissions from GHGRP and voluntary reporting, it is assumed there is likely an error, as this would imply negative emissions by GHGRP non-reporters. This was the case in 2015 and 2016. For these years, the GHGRP and voluntarily reported emissions from California are retained, and emissions from non-reporting utilities are estimated using a California-specific SF_6 emissions rate, which is based on CARB emission data. The California SF_6 emissions rate of 0.41 lbs SF_6 per transmission mile is found by taking the average of CARB emissions divided by the total California transmission mileage in years where CARB estimates are larger. Emissions from California non-reporting utilities are then found by multiplying the California SF_6 emissions rate by the California transmission mileage from non-reporting utilities. This methodology is also used if CARB has not published emissions estimates for a particular year. CARB has not yet published estimates for 2022.

Table 4-133: California GHGRP and Voluntarily Reported SF_6 Emissions Compared to CARB's SF_6 Emissions (MMT CO_2 Eq.)

	2011	2015	2016	2017	2018	2019	2020	2021	2022
CA GHGRP and Voluntary	0.19	0.16	0.24	0.12	0.11	0.14	0.20	0.14	0.15
CARB (CARB 2023)	0.24	0.14	0.10	0.18	0.14	0.17	0.24	0.24	NE
Final CA	0.24	0.21	0.29	0.18	0.14	0.17	0.24	0.24	0.20

NE (Not Estimated)

Total Industry Emissions

Total electric power system emissions from 1999 through 2022 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), the GHGRP-only reported emissions, off-ramping GHGRP Facilities (non-reporters), non-reporters who eventually report to GHGRP, and the non-reporting utilities' emissions (except California). Then, the California GHGRP and voluntarily reported emissions are subtracted from the total and replaced with CARB's emissions (or GHGRP and voluntarily reported emissions plus California non-reporting utilities' emissions).

Non-Partner Transmission Miles

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, 2012, and 2016 were obtained from the 2001, 2004, 2007, 2010, 2013, and 2017 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013, and 2017). For 2019 to 2022 non-reporter transmission mileage was derived by subtracting reported transmission mileage data from the total U.S.

transmission mileage from 2019 to 2022 HIFLD Data (HIFLD 2019, 2020, 2021, and 2022). The following trends in transmission miles have been observed over the time series:

- The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by 0.20 percent between 2003 and 2006.
- The U.S. transmission system's annual growth rate grew to 1.7 percent from 2006 to 2009 as transmission miles increased by more than 33,000 miles.
- The annual growth rate for 2009 through 2012 was calculated to be 1.4 percent as transmission miles grew yet again by over 29,000 miles during this time period.
- The annual transmission mile growth rate for 2012 through 2016 was calculated to be 0.2 percent, as transmission miles increased by approximately 5,500 miles.
- The annual transmission mile growth rate for 2016 through 2020 was calculated to be 0.9 percent, as transmission miles increased by approximately 26,000 miles.
- The annual transmission mile growth rate for 2020 through 2021 was calculated to be 2.2 percent, as transmission miles increased by approximately 16,000 miles.
- The annual transmission mile growth rate for 2021 through 2022 was calculated to be 0.7 percent, as transmission miles increased by approximately 5,500 miles.

Transmission miles for each year for non-reporters were calculated by interpolating between UDI reported values obtained from the 2001, 2004, 2007, 2010, 2013 and 2017 UDI directories and HIFLD data for 2019 and subsequent years. In cases where a non-reporter previously reported the GHGRP or the Partnership, transmission miles were interpolated between the most recently reported value and the next available UDI value.

1990 through 2022 Emissions from Manufacture of Electrical Equipment

Three different methods were used to estimate 1990 to 2022 emissions from original electrical equipment manufacturers (OEMs).

- OEM SF_6 emissions from 1990 through 2000 were derived by assuming that manufacturing emissions equaled 10 percent of the quantity of SF_6 provided with new equipment. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002). The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000.
- OEM SF_6 emissions from 2000 through 2010 were estimated by (1) interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs through the GHGRP (5.7 percent), and (2) estimating the quantities of SF_6 provided with new equipment for 2001 to 2010. The quantities of SF_6 provided with new equipment were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (156.5 MMT CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. Additionally, to obtain the 2011 emission rate (necessary for estimating 2001 through 2010 emissions), the estimated 2011 emissions (estimated using the third methodology listed below) were divided by the estimated total quantity of SF_6

provided with new equipment in 2011. The 2011 quantity of SF_6 provided with new equipment was estimated in the same way as the 2001 through 2010 quantities.

- OEM CF_4 emissions from 1991 through 2010 were estimated by using an average ratio of reported SF_6 and CF_4 emissions from 2011 through 2013. This ratio was applied to the estimated SF_6 emissions for 1991 through 2010 to arrive at CF_4 emissions. CF_4 emissions are estimated starting in 1991 and assumed zero prior to 1991 based on the entry of the CF_4/SF_6 gas mixture into the market (Middleton 2000).
- OEM emissions from 2011 through 2022 were estimated using the SF_6 and CF_4 emissions from OEMs reporting to the GHGRP, and an assumption that these reported emissions account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs (those that report and those that do not).
- OEM SF_6 emissions from facilities off-ramping from the GHGRP were determined by extrapolation. First, emission growth rates were calculated for each reporting year for each OEM reporting facility as well as an average emissions growth rate (2011 through 2022). Averages of reported emissions from last three consecutive reporting years were multiplied by the average growth rate for each off-ramping OEM to estimate emissions for the non-reporting year(s).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

To estimate the uncertainty associated with emissions of SF_6 and CF_4 from electrical equipment, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or EPA's GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of +/- 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 4.5 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 7.4 percent.

As discussed below, EPA has substantially revised its method for estimating emissions from non-Reporters, assuming that the average emission rate of non-Reporters has declined much more slowly than the average emission rate of reporting facilities rather than declining at the same rate. This assumption brings the U.S. SF_6 emissions estimated in this *Inventory* into better agreement with the U.S. SF_6 emissions inferred from atmospheric observations. However, it must be emphasized that the actual emission rates of non-Reporters remain unknown. It is possible that they are lower or even higher than estimated here. One possibility is that SF_6 sources other than electric power systems are contributing to the emissions inferred from atmospheric observations, implying that the emissions from non-Reporters are lower than estimated here. Another is that the emissions inferred from atmospheric measurements are over- (or under-) estimated, implying that emissions from non-Reporters could be either lower or higher than estimated here. These uncertainties are difficult to quantify and are not reflected in the estimated uncertainty below. The estimated uncertainty below accounts only for the two sources of uncertainty associated with the regression equations used to estimate emissions in 2019 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) estimates of SF_6 and CF_4 emissions from OEMs reporting to EPA's GHGRP, and (2) the assumption on the percent share of OEM emissions from OEMs reporting to EPA's GHGRP.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 1-57. electrical equipment emissions were estimated to be between 3.8 and 6.4 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 25 percent below and 25 percent above the emission estimate of 5.1 MMT CO_2 Eq. CF_4 emissions were estimated to be between 0.000006 and 0.000009 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 20 percent below and 20 percent above the emission estimate of 0.0000074 MMT CO_2 Eq.

Table 4-134: Approach 2 Quantitative Uncertainty Estimates for SF_6 and CF_4 Emissions from Electrical Equipment (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2022 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Equipment	SF_6	5.1	3.8	6.4	-25%	+25%
Electrical Equipment	CF_4	0.0000074	0.000006	0.000009	-20%	+20%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

In addition to the uncertainty quantified above for the 2022 estimate, there is uncertainty associated with the emission rates of GHGRP-only facilities before 2011 and of non-Reporters throughout the time series. As noted above in the discussion of the uncertainty of non-Reporters for 2022, these uncertainties are difficult to quantify.

There is also uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details. Category specific QC findings are described below.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[130] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

[130] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Additionally, EPA provides additional quality control for the SF_6 emissions estimates using atmospheric derived estimates for comparison. The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1: General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. Further, it identifies fluorinated gases as particularly suited for such comparisons. The *2019 Refinement* makes this conclusion for fluorinated gases based on their lack of significant natural sources,[131] their generally long atmospheric lifetimes, their well-known loss mechanisms, and the potential uncertainties in bottom-up inventory methods for some of their sources. Unlike non-fluorinated greenhouse gases (CO_2, CH_4, and N_2O), SF_6 has no significant natural sources; therefore, the SF_6 estimates derived from atmospheric measurements are driven overwhelmingly by anthropogenic emissions. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC (2019) Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC (2019) Volume 1, Chapter 6). Emission estimates derived from atmospheric measurements of SF_6 made at NOAA and described in Hu et al. (2022) were used to perform a comparison to the inventory estimates. This comparison resulted in changes to historical emission estimates, as more thoroughly described in the previous *Inventory* cycle (EPA 2022). No further changes were made to the electrical equipment estimates for the current (i.e., 1990 through 2022) *Inventory* based on this comparison.

Recalculations Discussion

Several updates to activity data led to recalculations of previous *Inventory* results. The major updates are as follows:

- As discussed in the methodology above, CARB estimates of SF_6 emissions from electrical equipment in California were used as California's contribution to the national total starting in 2011, except in cases where CARB emissions were lower than GHGRP and voluntarily reported emissions from California, or in years where CARB has not published SF_6 emissions estimates.
- Updates were made to reporter emissions where facilities had resubmitted data.
- A correction was made to estimate 2021 nameplate capacities for two off-ramping utilities, which off-ramped in 2021; these estimations were inadvertently omitted in the previous *Inventory*.
- SF_6 emissions from electrical equipment manufacturing was corrected due to an erroneous data pull in the previous *Inventory*. This caused emissions to increase in years 2011 through 2019.
- Partner transmission mileage used for calculating average share of Partner utilities across the time series and for estimating nameplate capacity for non-reporting utilities was corrected. The calculation was previously referencing partner transmission mileage for the prior year for 2013 through 2021.

Planned Improvements

EPA plans to revisit the methodology for determining emissions from the manufacture of electrical equipment, in particular, the assumption that emissions reported by OEMs account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs. Additional market research will be required to confirm or modify the assumptions regarding the portion of industry not reporting to the GHGRP program.

[131] See Harnisch and Eisenhauer (1998).

4.27 SF_6 and PFCs from Other Product Use (CRT Source Category 2G.2)

There are a variety of other products and processes that use fluorinated greenhouse gases. This section estimates emissions of sulphur hexafluoride (SF_6) and perfluorocarbons (PFCs) from other product use (CRT Source Category 2G.2), including military and scientific applications. Many of these applications utilize SF_6 or PFCs to exploit their unique chemical properties, such as the high dielectric strength of SF_6 and the stability of PFCs. Emission profiles from these processes may vary greatly, ranging from immediate and unavoidable release of all of the chemical to largely avoidable, delayed release from leak-tight products after decades of use.

Military applications employ SF_6 and PFCs in many processes, such as the use of SF_6 in the radar systems of military reconnaissance planes of the Boeing E-3A type, commonly known as Airborne Warning and Control Systems (AWACS). These systems use SF_6 to prevent electric flashovers in the hollow conductors of the antenna, where voltages can reach up to 135 kilovolts (kV). During ascent of the planes, SF_6 is automatically released from the AWACS to maintain appropriate pressure difference between the system and the outside air. During descent, the system is automatically charged with SF_6 from an SF_6 container on board. Most emissions occur during ascent but may also occur from system leakage during other phases of flight or during time on the ground. Emissions from AWACS are largely dependent on the number of active planes and sorties (take-offs) per year.

Other uses of SF_6 in military applications include the oxidation of lithium in navel torpedoes and infrared decoys. SF_6 has also been documented for use in the quieting of torpedo propellers, as well as a by-product of the processing of nuclear material for the production of fuel and nuclear warheads.

Military electronics are believed to be a key application for PFC heat transfer fluids, particularly in areas such as ground and airborne radar avionics, missile guidance systems, and sonar. PFCs may also be used to cool electric motors, especially for equipment where noise reduction is a priority (e.g., submarines). The specific PFCs used in military applications are similar to heat transfer fluids identified in the electronics industry (see Section 4.24). PFCs are typically contained in a closed system, so the emissions are most likely to occur during the manufacture, maintenance, and disposal of equipment.

SF_6 and PFCs are also employed in several scientific applications, such as for use in particle accelerators. Particle accelerators can be found in university and research settings, as well as in industrial and medical applications. SF_6 is typically used as an insulating gas and is operated in a vessel exceeding atmospheric pressure. The amount of SF_6 used in particle accelerators is largely dependent on the terminal voltage of the unit. Emissions of SF_6 typically occur when SF_6 is transferred to storage tanks while maintenance is occurring, when pressure relief valves are actuated, and through slow leaks. The emission and charge assumptions for industrial and medical particle accelerators differ from those of university and research accelerators, as discussed in the methodology below. PFCs (particularly PFC-14) may also be used in particle accelerators as particle detectors or counters (Workman 2022).

SF_6 may also be employed in other high-voltage scientific equipment, including lasers, x-rays, and electron microscopes. SF_6 emission estimates for this equipment were not disaggregated from particle accelerators for this *Inventory*.

There is a range of unidentified processes that also use SF_6 and PFCs, such as R&D activities. PFCs are likely used primarily as heat transfer fluids (HTFs). Emissions reported for these unknown activities group under “Other Scientific Applications”.

Emissions of SF_6 and PFCs from the applications outlined above are presented in Table 4-135.

Table 4-135: SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.6	0.6	0.4	0.4	0.3	+	0.3
Total AWACs	**0.6**	**0.6**	**0.4**	**0.4**	**0.3**	**+**	**0.3**
SF_6	0.3	0.3	0.0	0.0	0.0	0.0	0.0
PFCs	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Total Other Military Applications	**0.4**	**0.4**	**0.2**	**0.2**	**0.2**	**0.1**	**0.2**
SF_6	0.4	0.5	0.4	0.2	0.1	0.2	0.2
PFC-14	+	+	+	+	+	+	+
Total Particle Accelerators	**0.4**	**0.5**	**0.4**	**0.2**	**0.1**	**0.2**	**0.2**
SF_6	+	+	+	+	0.1	0.2	0.1
PFCs	+	+	+	+	+	+	+
Total Other Scientific Applications	**+**	**+**	**+**	**+**	**0.1**	**0.2**	**0.1**
Total Other Product Use	**1.4**	**1.5**	**0.9**	**0.8**	**0.7**	**0.5**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: PFC subtotals include estimates for HFEs. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions are based primarily on data reported through the Federal Energy Management Program (FEMP). However, the availability of data from FEMP differs across the 1990 through 2022 time series. Consequently, additional emission estimates were made through utilizing methodologies from the IPCC. Emissions from military applications and scientific applications were estimated separately, and the approaches are described immediately below.

Military Applications

1990 through 2007

FEMP data was not readily available for the 1990 to 2007 period as the first reporting year was in 2008. Thus for this period, estimated SF_6 emissions from AWACS were calculated based using the IPCC Tier 1 methodology (IPCC 2006). IPCC provided a default emissions factor of 740kg of SF_6 per plane per year. It was assumed that the U.S. AWAC fleet between 1990 through 2022 remained constant at 33 planes. The IPCC methodology was utilized for all years from 1990 to 2007.

Emissions for other military applications were estimated by taking the average of the emissions estimated for other applications as described in the next section for first five FEMP reporting years (i.e., 2008 through 2012) and held constant between 1990 through 2007. Emissions from AWACS were not specifically reported by FEMP; the estimates developed for AWACS using the IPCC methodology above were employed to determine emissions from remaining unidentified military applications.

2008 through 2021

For the period 2008 through 2021, the Department of Defense (DOD) reported emission data through FEMP which were used to develop estimates for SF_6 and PFCs from other military applications. SF_6 emission estimates developed for AWACS using the IPPC Tier 1 methodology (see 1990 through 2007) were compared against SF_6 emissions reported by DOD between 2008 and 2021. In years where SF_6 emissions reported by DOD was smaller than those estimated using the IPCC Tier 1 methodology, DOD-reported emissions were assumed to account for total AWAC emissions; in years where DOD emissions were greater than the calculated AWAC emissions, the remainder is assumed to be from other SF_6 applications.

Emissions from PFCs, HFEs, and other perfluoro compounds are directly reported by DOD. In years where there are data gaps from FEMP between two reporting years, expected emissions were interpolated.

2022

Estimates for emissions from AWACS and other military uses for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021).

Scientific Applications

1990 through 2007

For the period 1990 through 2007, where no reported data is available from the Department of Energy (DOE), estimates for emissions of SF_6 and PFCs from other product use at Department of Energy Laboratories were determined by taking an average of the first five reporting years (i.e., 2008 through 2012) and held constant from 1990 to 2007.

SF_6 emissions from other (non-DOE) research and industrial particle accelerators in the United States was calculated based on the IPCC Tier 1 methodology for estimating emissions from industrial and university/research particle accelerators. Default emission factors, charge sizes, and usage rates are provided by size and type of accelerator in the IPCC methodology. These default assumptions were multiplied against the number of particle accelerators estimated to be active in the United States by year. This methodology remained the same from 1990 to 2007.

2008 through 2021

For the period 2008 through 2021, SF_6 and PFC emissions from government particle accelerators and other scientific equipment were developed using DOE-reported emissions. SF_6 and PFC emissions from particle accelerators were directly reported by DOE. Other fugitive emissions reported by DOE for SF_6 were assumed to represent emissions from particle accelerators and other scientific equipment, as well as two DOE-managed power facilities (WAPA and BPA).[132] Emissions from these two facilities were subtracted out to present only SF_6 emissions from scientific equipment. Reported fugitive emissions for PFC-14 were assumed to wholly represent particle accelerator applications. SF_6 emissions from non-government particle accelerators were estimated using the IPPC Tier 1 methodology used for 1990 through 2007.

Process emissions from other applications for SF_6 and PFCs were reported by DOE for activities such as R&D, and these emissions were summed by gas. However, the estimates presented here do not include emissions reported for semiconductor research and manufacture, or from refrigeration and air conditioning. Emissions from additional PFCs, HFEs, and other perfluoro compounds are directly reported by DOE and are reported as "Other Applications." Emissions reported to FEMP were generally calculated based on consumption data. In a number of years, negative values for emissions were reported due to more gas being returned to supply than purchased in a given year. When negative values were reported, EPA took the average of that year and the proceeding and following year and applied that value to all three years. This 3-year average was assumed to be more representative of actual emissions.

In years where there are data gaps between two reporting years, emissions were interpolated.

2022

For emission estimates developed using DOE-reported emissions, estimates for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021). SF_6 emissions from non-government

[132] DOE-reported fugitive emissions for SF_6 and PFCs includes emissions from high-voltage scientific equipment such as lasers, x-rays, and electron microscopes. Emissions from this equipment is included in the particle accelerators total.

particle accelerators were estimated using the same IPPC Tier 1 methodology used for 2008 through 2021.

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from other product use, represented in equation form as:

Equation 4-27: Total Emissions from Other Product Use

$$\begin{aligned}&\text{Total Emissions } (E_T)\\ &\quad = \text{ Military Applications } SF_6 \text{ and PFC Emissions } \left(E_{Military}\right)\\ &\quad + \text{ Scientific Applications of } SF_6 \text{ and PFC Emissions } \left(E_{Scientific}\right)\end{aligned}$$

The uncertainty in the total emissions for other product use, presented in Table 4-124 below, results from the convolution of two distributions of emissions, namely from military applications and scientific applications. The approaches for estimating uncertainty in each of the sources are described below:

Military Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from military applications, represented in equation form as:

Equation 4-28: Total Emissions from Military Applications

$$\begin{aligned}&\text{Military Applications } SF_6 \text{ and PFC Emissions } \left(E_{Military}\right)\\ &\quad = \text{ Military AWACS } SF_6 \text{ Emissions } \left(E_{AWACS,SF_6,Military}\right)\\ &\quad + \text{ Other Military Applications } SF_6 \text{ Emissions } \left(E_{Other,SF_6,Military}\right)\\ &\quad + \text{ Other Military Applications PFC Emissions } \left(E_{Other,PFC,Military}\right)\end{aligned}$$

The uncertainty in $E_{Military}$ results from the convolution of three distributions of emissions, $E_{AWACS,SF6,Military}$, $E_{Other,SF6,Military}$, and $E_{Other,PFC,Military}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Military}$ are described in the remainder of this section.

The uncertainty estimate of $E_{AWACS,SF6,Military}$, or SF_6 emissions from AWACS, is developed based on the number of AWACS in commission in the United States and the per-plane emission factor. The estimated number of active planes installed with AWACS is 33, although estimates range between 31 and 35. The IPCC provides a per-plane emission factor of 740 kg of SF_6 per plane annually and estimates the uncertainty to have bounds of ±14 percent.

The uncertainty in $E_{Other,SF6,Military}$ and $E_{Other,PFC,Military}$, or SF_6 and PFC emissions from other military applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Defense uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from military AWACS and other military applications is convolving the distribution of reported emissions, emission factors, and number of AWACS using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported emissions and emission factors are assumed to be normally distributed, and the number of AWACS is assumed to have a uniform distribution since this is a discrete number of planes. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

Scientific Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from scientific applications,

represented in equation form as:

Equation 4-29: Total Emissions from Scientific Applications

$$\begin{aligned}&\text{Scientific Applications } SF_6 \text{ and PFC Emissions } \left(E_{Scientific}\right)\\&= \text{ Particle Accelerators } SF_6 \text{ Emissions } \left(E_{Accelerators,SF_6,Scientific}\right)\\&+ \text{ Particle Accelerators PFC Emissions } \left(E_{Accelerators,PFC,Military}\right)\\&+ \text{ Other Scientific Applications } SF_6 \text{ Emissions } \left(E_{Other,SF_6,Scientific}\right)\\&+ \text{Other Scientific Applications PFC Emissions } \left(E_{Other,PFC,Scientific}\right)\end{aligned}$$

The uncertainty in $E_{Scientific}$ results from the convolution of four distributions of emissions, $E_{Accelerators,SF6,Scientific}$, $E_{Accelerators,PFC,Military}$, $E_{Other,SF6,Scientific}$, and $E_{Other,PFC,Scientific}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Scientific}$ are described in the remainder of this section.

The uncertainty estimate of $E_{Accelerators,SF6,Scientific}$ and $E_{Accelerators,PFC,Scientific}$, or SF_6 and PFC emissions from particle accelerators, is developed based on fugitive and process emissions reported by the Department of Energy and emission estimates from the number active university and industrial particle accelerators in the United States. The number of active particle accelerators in the United States for the time series 1990 through 2022 was determined using expert judgment; default emission factors and charge sizes for particle accelerators of various sizes were provided by IPCC guidelines. Emissions of SF_6 from electrical transmission and distribution equipment were removed from total emissions estimates for this source category, as they are reported elsewhere in the *Inventory.*

The uncertainty in $E_{Other,SF6,Scientific}$ and $E_{Other,PFC,Scientific}$, or SF_6 and PFC emissions from other scientific applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Energy uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from particle accelerators and other scientific applications is convolving the distribution of calculated emissions, emission factors, number of accelerators using Monte Carlo simulation. Similarly, the distributions of the reported emissions and emission factors for this Monte Carlo simulation are assumed to be normally distributed, and the number of particle accelerators and other scientific applications is assumed to have a uniform distribution since this is a discrete number of accelerators. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

The emissions estimate for total U.S. SF_6 and PFC emissions from other product use were estimated to be between 0.5 and 1.1 MMT CO_2 Eq. at a 95 percent CI level. This range represents 36 percent below and 38 percent above the 2022 emission estimate of 0.8 MMT CO_2 Eq. for all emissions from others product use. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-136: Approach 2 Quantitative Uncertainty Estimates for SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Other Product Use	SF_6 and PFC	0.8	0.5	1.1	-36%	+38%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

4.28 Nitrous Oxide from Product Uses (CRT Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. This reporting category (2G3) includes exhalation emissions of N_2O that arise from medical applications and evaporative emissions of N_2O from use as a propellant in aerosol products primarily in food industry. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2021). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2022 was approximately 15 kt (see Table 4-137).

Table 4-137: N_2O Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	16	15	15	15	15	15	15

Nitrous oxide emissions were 3.8 MMT CO_2 Eq. (14 kt N_2O) in 2022 (see Table 4-138). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-138: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	3.8	3.8	3.8	3.8	3.8	3.8	3.8

Table 4-139: N_2O Emissions from N_2O Product Usage (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	14	14	14	14	14	14	14

Methodology and Time-Series Consistency

Emissions from N_2O product uses are calculated using a country-specific methodology that is consistent with *2006 IPCC Guidelines* and based on available data. The *2006 IPCC Guidelines* do not define tier methodologies for this source category. Emissions of N_2O are estimated using the national N_2O production by subcategory use or application, the share of the subcategory, and the appropriate emission rate for each category. The following equation is adapted from Equation 8.24 of the *2006 IPCC Guidelines*:

Equation 4-30: N_2O Emissions from Product Use

$$E_{pu} = \sum_{a} (P \times S_a \times ER_a)$$

where,

E_{pu} = N_2O emissions from product uses, metric tons

P = Total U.S. production of N_2O, metric tons

a = specific application

S_a = Share of N_2O usage by application *a*

ER_a = Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end-use represents the share of national N_2O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2020, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other subcategories, including semiconductor manufacturing, atomic absorption spectrometry, sodium azide production, auto racing, and blowtorches, used the remainder of the N_2O produced. This subcategory breakdown changed slightly in the mid-1990s. For instance, the small share of N_2O usage in the production of sodium azide declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). For 1990 through 1996, N_2O usage was allocated across the following subcategories: medical applications, food processing propellant, and sodium azide production. A usage emissions rate was then applied for each subcategory to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were assumed to release emissions into the atmosphere that are not captured under another source category, and therefore these subcategories were the only usage subcategories with emission rates. Emissions of N_2O from semiconductor manufacturing are described in Section 4.24 and reported under CRT Source Category 2H3. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed or reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for

1996 was specified as a range in two data sources (Heydorn 1997; Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2002) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2002) data are considered more industry-specific and current; therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2002). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the lack of publicly available data, production estimates for years 2004 through 2022 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the lack of publicly available data, the share of total quantity of N_2O usage data for years 2004 through 2021 was assumed to equal the 2003 value. The emission factor for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997) and confirmed by a N_2O industry expert (Tupman 2002). The emission factor for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emission factor for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The overall uncertainty associated with the 2022 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively. The uncertainty associated with N_2O production data is ±25 percent, and a uniform probability density function is assigned, based on expert judgment (RTI 2023). The uncertainty associated with the market share for the medical/dental subcategory is ±0.56 percent, and uncertainty for the market share of food propellant subcategory is ±25 percent, both based on expert judgment (RTI 2023). Uncertainty for emission factors was assumed to be zero, and using this suggested uncertainty provided in the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-140. Nitrous oxide emissions from N_2O product usage were estimated to be between 2.9 and 4.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 3.8 MMT CO_2 Eq.

Table 4-140: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O from Product Uses	N_2O	3.8	2.9	4.6	-24%	+24%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

EPA recently initiated an evaluation of alternative production statistics for cross-verification and updating time-series activity data, emission factors, assumptions, etc., and a reassessment of N_2O product use subcategories that accurately represent trends. This evaluation includes conducting a literature review of publications and research that may provide additional details on the industry. This work remains ongoing, and thus far no additional sources of data have been found to update this category.

Pending additional resources and planned improvement prioritization, EPA may also evaluate production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

Finally, for future Inventories, EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing CBI and time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this *Inventory*. This is a lower priority improvement, and EPA is still assessing the possibility of incorporating aggregated GHGRP CBI data to estimate emissions; therefore, this planned improvement is still in development and not incorporated in the current *Inventory* report.

4.29 Industrial Processes and Product Use Sources of Precursor Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various greenhouse gas precursors. The reporting requirements of the Paris Agreement and the UNFCCC[133] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse gases (e.g., ozone) and atmospheric aerosol (e.g., particulate sulfate). Combustion byproducts such as CO and NO_x are emitted from industrial applications that employ thermal incineration as a control technology. NMVOCs, commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based products, and can also result from the product storage and handling.

[133] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

Accidental releases of precursors associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of hydrofluorocarbons (HFCs) and small amounts of hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances and the Electronics Industry in this chapter.

Total emissions of NO_x, CO, NMVOCs, and SO_2 from non-energy industrial processes and product use from 1990 to 2022 are reported in Table 4-141.

Table 4-141: NO_x, CO, NMVOC, and SO_2 Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
NO_x	**774**	**672**	**461**	**440**	**393**	**403**	**389**
Mineral Industry	160	200	118	114	101	99	95
Other Industrial Processes[a]	326	355	218	206	187	189	184
Metal Industry	96	58	63	60	52	60	56
Chemical Industry	192	80	61	59	54	55	53
CO	**4,099**	**1,701**	**1,022**	**1,011**	**855**	**902**	**897**
Metal Industry	2,261	707	447	448	340	355	335
Other Industrial Processes[a]	564	662	332	331	294	309	329
Mineral Industry	182	120	111	106	96	95	95
Chemical Industry	1,093	211	132	126	125	142	138
NMVOCs	**6,982**	**3,668**	**3,119**	**2,996**	**3,366**	**3,508**	**3,505**
Other Industrial Processes[a]	6,270	3,396	3,003	2,883	3,261	3,398	3,401
Chemical Industry	601	221	88	86	81	84	79
Mineral Industry	9	10	7	7	6	6	6
Metal Industry	102	40	21	20	17	19	19
SO_2	**1,488**	**776**	**335**	**309**	**266**	**274**	**261**
Other Industrial Processes[a]	474	256	145	134	120	126	119
Chemical Industry	283	242	106	97	83	83	75
Mineral Industry	166	138	25	25	26	28	28
Metal Industry	566	140	58	53	37	38	39

[a] Other Industrial Processes includes storage and transport, other industrial processes (manufacturing of agriculture, food, and kindred products; wood, pulp, paper, and publishing products; rubber and miscellaneous plastic products; machinery products; construction; transportation equipment; and textiles, leather, and apparel products), and miscellaneous sources (catastrophic/accidental release, other combustion (structural fires), health services, repair shops, and fugitive dust). It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

Note: Totals by gas may not sum due to independent rounding.

Source: (EPA 2023a). Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2020 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 4-141, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs were recategorized from NEI Emissions Inventory System (EIS) sectors to source categories more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC based on

discussions between the EPA GHG Inventory and NEI staff (see crosswalk documented in Annex 6.3).[134] EIS sectors mapped to the IPPU sector categories in this report include: chemical and allied product manufacturing, metals processing, storage and transport, solvent utilization, other industrial processes, and miscellaneous sources. As described in the NEI Technical Support Documentation (TSD) (EPA 2023c), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

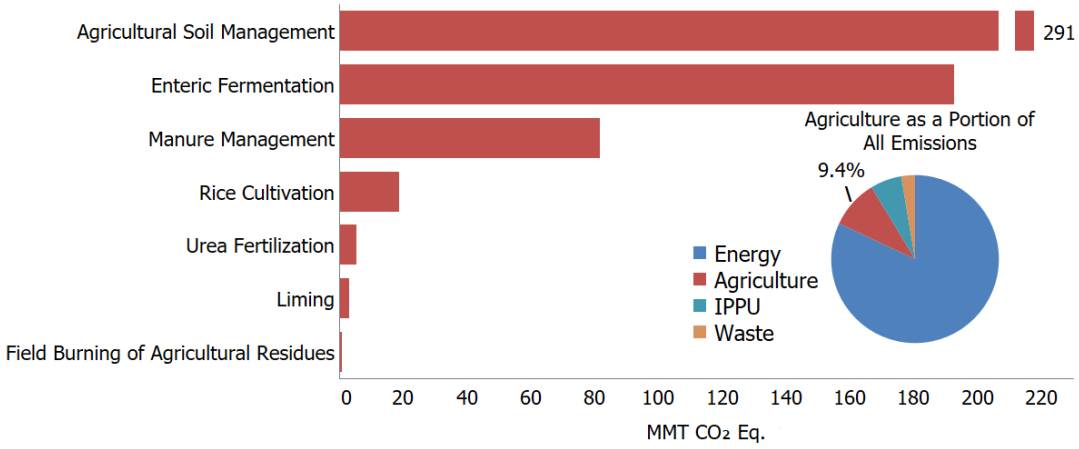
Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2021, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends web site (EPA 2023a; EPA 2023c). A quantitative uncertainty analysis was not performed.

[134] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRTs), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of methane (CH_4) from enteric fermentation, livestock manure management, rice cultivation and field burning of agricultural residues; nitrous oxide (N_2O) emissions from agricultural soil management, livestock manure management, and field burning of agricultural residues; as well as carbon dioxide (CO_2) emissions from liming and urea fertilization (see Figure 5-1). Additional CO_2, CH_4 and N_2O fluxes from agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, management on grasslands, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. Carbon dioxide emissions from stationary and mobile on-farm energy use and CH_4 and N_2O emissions from stationary on-farm energy use are reported in the Energy chapter under the Industrial sector emissions. Methane and N_2O emissions from mobile on-farm energy use are reported in the Energy chapter under mobile fossil fuel combustion emissions.

Figure 5-1: 2022 Agriculture Sector Greenhouse Gas Emission Sources



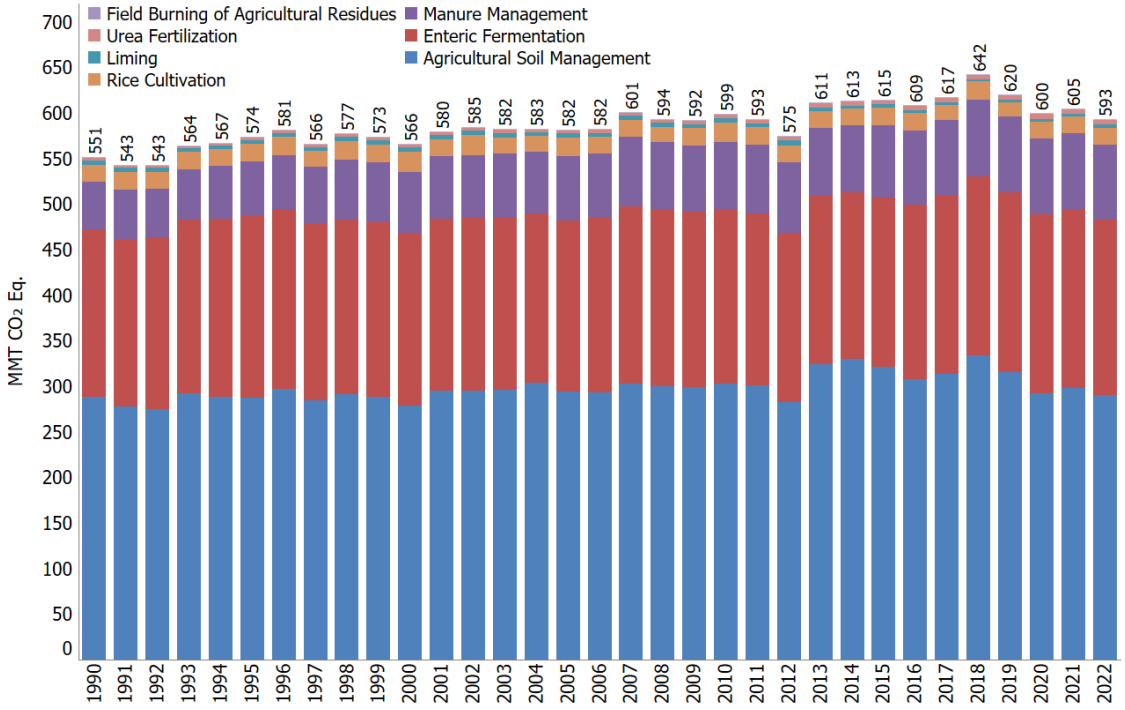
In 2022, the Agriculture sector was responsible for emissions of 593.4 MMT CO_2 Eq.,[1] or 9.4 percent of total U.S. greenhouse gas emissions. Emissions of N_2O by agricultural soil management through activities such as fertilizer

[1] Following the current reporting requirements under the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC), this Inventory report presents CO_2 equivalent values based on the IPCC *Fifth Assessment Report* (AR5) GWP values. See the Introduction chapter as well as Chapter 9 for more information.

application and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N_2O emissions, accounting for 74.6 percent, and the largest source of emissions from the Agriculture sector, accounting for 49.0 percent of total sector emissions. Methane emissions from enteric fermentation and manure management represented 27.4 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, and 32.5 and 10.9 percent of Agriculture sector emissions, respectively. Of all domestic animal types, beef and dairy cattle were the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Manure management and field burning of agricultural residues were also small sources of N_2O emissions. Urea fertilization and liming each accounted for 0.1 percent of total CO_2 emissions from anthropogenic activities.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2022, CO_2 and CH_4 emissions from agricultural activities increased by 21 percent and 14.5 percent, respectively, while N_2O emissions from agricultural activities fluctuated from year to year but increased by 1.9 percent overall. Trends in sources of agricultural emissions over the 1990 to 2022 time series are shown in Figure 5-2.

Figure 5-2: Trends in Agriculture Sector Greenhouse Gas Emission Sources



Each year, some emission estimates in the Agriculture sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 through 2021) to ensure that the trend is accurate. This year's key improvements include: manure management: updates to beef feedlot and poultry waste management system (WMS) data; field burning of agricultural residues: addition of residue burning from sugarcane. For more information on specific methodological updates, please see the Recalculations Discussions within the respective source category sections of this chapter. In total, the methodological and historic data improvements made to the Agriculture sector in this *Inventory* increased greenhouse gas emission estimates by an average of 5.3 MMT CO_2 Eq. (0.9 percent) across the time series.

Emissions reported in the Agriculture chapter include those from all states; however, for Hawaii and Alaska some agricultural practices that can increase nitrogen availability in the soil, and thus cause N_2O emissions, are not

included (see chapter sections on Uncertainty and Time-Series Consistency and Planned Improvements for more details). Emissions from the Agriculture sector occurring in U.S. Territories and the District of Columbia are not estimated due to incomplete data, with the exception of urea fertilization in Puerto Rico. EPA continues to identify and review available data on an ongoing basis to include agriculture emissions from U.S. Territories, to the extent they are occurring, in future *Inventories*. Other minor outlying U.S. Territories in the Pacific Islands have no permanent populations (e.g., Baker Island) and therefore EPA assumes no agricultural activities are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**7.1**	**7.9**	**7.2**	**7.2**	**8.0**	**7.6**	**8.6**
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3
Liming	4.7	4.4	2.2	2.2	2.9	2.4	3.3
CH_4	**241.7**	**264.4**	**285.0**	**280.2**	**282.4**	**281.8**	**276.8**
Enteric Fermentation	183.1	188.2	196.8	197.3	196.3	196.5	192.6
Manure Management	39.1	55.0	67.7	66.7	66.9	66.4	64.7
Rice Cultivation	18.9	20.6	19.9	15.6	18.6	18.3	18.9
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.7	0.6	0.6	0.6
N_2O	**302.3**	**309.5**	**350.2**	**332.6**	**309.2**	**315.3**	**308.0**
Agricultural Soil Management	288.8	294.1	333.4	315.6	292.1	298.0	290.8
Manure Management	13.4	15.2	16.6	16.8	16.9	17.1	17.0
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**551.1**	**581.8**	**642.4**	**620.1**	**599.7**	**604.8**	**593.4**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**7,106**	**7,856**	**7,176**	**7,237**	**8,019**	**7,616**	**8,595**
Urea Fertilization	2,417	3,504	4,936	5,034	5,132	5,229	5,327
Liming	4,690	4,351	2,240	2,203	2,887	2,387	3,268
CH_4	**8,633**	**9,444**	**10,179**	**10,008**	**10,087**	**10,066**	**9,885**
Enteric Fermentation	6,539	6,722	7,028	7,045	7,010	7,017	6,878
Manure Management	1,398	1,964	2,418	2,382	2,390	2,373	2,312
Rice Cultivation	677	735	711	558	664	653	674
Field Burning of Agricultural Residues	19	23	22	23	22	22	22
N_2O	**1,141**	**1,168**	**1,322**	**1,255**	**1,167**	**1,190**	**1,162**
Agricultural Soil Management	1,090	1,110	1,258	1,191	1,102	1,124	1,097
Manure Management	50	57	63	63	64	65	64
Field Burning of Agricultural Residues	1	1	1	1	1	1	1

Note: Totals by gas may not sum due to independent rounding.

Box 5-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*). Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The

presentation of emissions provided in the Agriculture chapter does not preclude alternative examinations (e.g., economic sectors). Rather, this chapter presents emissions in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follow this common format and provide an explanation of the application of methods used to calculate emissions from agricultural activities.

5.1 Enteric Fermentation (CRT Source Category 3A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.[2]

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2022 were 192.6 MMT CO_2 Eq. (6,878 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2022. Emissions from dairy cattle in 2022 accounted for 25 percent, and the remaining methane emissions were from swine, horses, sheep, goats, American bison, mules and asses.[3]

[2] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

[3] Enteric fermentation emissions from poultry are not estimated because no IPCC method has been developed for determining enteric fermentation CH_4 emissions from poultry; at this time, developing a country-specific method would require a disproportionate amount of resources given the small magnitude of this source category. Enteric fermentation emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2018	2019	2020	2021	2022
Beef Cattle	132.8	139.6	141.2	141.7	140.5	140.3	137.0
Dairy Cattle	43.3	41.3	48.6	48.5	48.8	49.4	48.9
Swine	2.3	2.6	3.1	3.2	3.2	3.1	3.1
Horses	1.1	2.0	1.4	1.3	1.2	1.1	1.0
Sheep	2.9	1.5	1.3	1.3	1.3	1.3	1.3
Goats	0.6	0.7	0.7	0.7	0.7	0.7	0.7
American Bison	0.1	0.5	0.4	0.4	0.5	0.5	0.5
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**183.1**	**188.2**	**196.8**	**197.3**	**196.3**	**196.5**	**192.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt CH_4)

Livestock Type	1990	2005	2018	2019	2020	2021	2022
Beef Cattle	4,742	4,986	5,042	5,062	5,018	5,010	4,891
Dairy Cattle	1,547	1,473	1,737	1,732	1,743	1,764	1,748
Swine	81	92	110	115	115	111	110
Horses	40	70	48	46	43	40	37
Sheep	102	55	47	47	47	47	46
Goats	23	26	24	25	25	25	25
American Bison	4	17	15	16	16	17	17
Mules and Asses	1	2	3	3	3	3	3
Total	**6,539**	**6,722**	**7,028**	**7,045**	**7,010**	**7,017**	**6,878**

Note: Totals may not sum due to independent rounding.

From 1990 to 2022, emissions from enteric fermentation have increased by 5.2 percent. From 2021 to 2022, emissions decreased by 2 percent, largely driven by a decrease in beef cattle populations. While emissions generally follow trends in cattle populations, there are exceptions across the time series. For example, while dairy cattle emissions increased 13 percent over the entire time series, the population has declined by 4.5 percent, and milk production increased 45.9 percent (USDA 2021; USDA 2022). These trends indicate that while emissions per head are increasing, emissions per unit of product (i.e., meat, milk) are decreasing.

Generally, from 1990 to 1995 emissions from beef cattle increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef cattle populations increased, and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2007 to 2014, as populations again decreased, but increased from 2015 to 2018, consistent with another increase in population over those same years. Emissions and populations generally declined from 2018 to 2022, with a slight post-pandemic rebound in 2021.

Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy cattle population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets used by producers across the United States). Dairy cattle emissions continued to trend upward from 2007 to 2018, generally in line with dairy cattle population changes.

plans to include this emissions category in the *Inventory*. See Annex 5 for more information on significance of estimated camel emissions.

Regarding trends in other animals, populations of sheep have steadily declined, with an overall decrease of 55 percent since 1990. Horse populations peaked in 2007 and have been declining by an average of 4 percent annually since 2007, with their current population 6 percent lower than it was in 1990. Goat populations increased by about 20 percent through 2007 followed by a steady decrease through 2012. Since 2012, goat populations continue to increase by 1 percent annually. Swine populations have trended upward through most of the time series, increasing 43 percent from 1990 to 2020. However, swine populations decreased by around 5 percent from 2020 to 2022. The population of American bison more than quadrupled over the 1990 to 2022 time period, while the population of mules and asses increased by a factor of five.

Methodology and Time-Series Consistency

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were estimated using the IPCC Tier 1 approach, as suggested by the *2006 IPCC Guidelines* (see the Planned Improvements section).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation using IPCC's Tier 2 method, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation. In addition, variables and the resulting emissions are also available at the state level in Annex 3.10.

Inventory Methodology for Cattle

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
  - Calves
  - Heifer Replacements
  - Cows
- Beef Cattle
  - Calves
  - Heifer Replacements
  - Heifer and Steer Stockers
  - Animals in Feedlots (Heifers and Steer)
  - Cows
  - Bulls

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.10. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) *QuickStats* database (USDA 2023).

Diet characteristics were estimated by region for dairy, grazing beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 2006, 2007, and 2008 onward.[4] Base year Y_m values by region were estimated using Donovan (1999). As described in ERG (2016), a ruminant digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA-APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5- and 6-month-old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type in each state. More details are provided in Annex 3.10.

[4] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003 as well.

Non-Cattle Livestock

Emission estimates for other animal types were based on average emission factors (Tier 1 default IPCC emission factors) representative of entire populations of each animal type. The methodology is in accordance with the methodological decision tree for methane emissions from enteric fermentation (IPCC 2019). Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2022. Additionally, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

Annual livestock population data for 1990 to 2022 for sheep, swine, goats, horses, mules and asses, and American bison were obtained for available years from USDA-NASS (USDA 2023; USDA 2019). Horse, goat, and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019); the remaining years between 1990 and 2022 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992). American bison population estimates were available from USDA for 2002, 2007, 2012, and 2017 (USDA 2019) and from the National Bison Association (1999) for 1990 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and extrapolation beyond 2012, as described in more detail in Annex 3.10.

Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006; IPCC 2019). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison, the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

Uncertainty

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology based on a Monte Carlo stochastic simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 *Inventory* (i.e., 2003 submission to the UNFCCC). While there are plans to update the uncertainty to reflect recent methodological updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2022 emission estimates in this *Inventory*.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for *Inventory* estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the uncertainty analysis last conducted in 2001 because the Food and Agricultural Organization (FAO) of the United Nations population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are

drawn from the same USDA source as the other animal types[5], and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emission estimates at that time.

The uncertainty ranges associated with the activity data-related input variables were ±10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 5-5. Based on this analysis, enteric fermentation CH_4 emissions in 2022 were estimated to be between 171.4 and 227.2 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2022 emission estimate of 192.6 MMT CO_2 Eq.

As a comparison to the Approach 2, a quantitative uncertainty analysis for this source category was performed using the IPCC (2006) recommended Approach 1 based on simple error propagation. Enteric fermentation CH_4 emissions in 2022 were estimated to be between 132.6 and 252.6 MMT CO_2 Eq., which indicates a range of ±31 percent above and below the 2022 emission estimate of 192.6 MMT CO_2 Eq. A ±10 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±40 percent default uncertainty factor is applied to the emission factors (IPCC 2019).

Table 5-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	192.6	171.4	227.2	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2022 estimates.
[c] The overall uncertainty calculated in 2003, and applied to the 2022 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the *U.S. Inventory QA/QC Plan* outlined in Annex 8. Category-specific or Tier 2 QA procedures included independent review of emission estimate methodologies from previous *Inventories*.

As part of the quality assurance process, average implied emissions factors for U.S. dairy and beef cattle were developed based on CEFM output and compared to emission factors for other countries provided by IPCC (2006). This comparison is discussed in further detail in Annex 3.10.

Over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current *Inventory* utilizes the same transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in

[5] The change from using FAO data to USDA data for horse populations took place during the development of the 1990 through 2011 *Inventory*, published in 2013.

conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories.

Recalculations Discussion

In the previous *Inventory*, 1990 to 2020 estimates were retained from the 1990 through 2020 *Inventory*, and 2021 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current *Inventory*, the CEFM was used for cattle for all years, resulting in different estimates for 2021 than the prior *Inventory*.

For cattle, there were also changes to emissions resulting from activity data changes, including:

- The USDA published minor data revisions that EPA incorporated into the CEFM:
    - Calf birth data were revised for 2020;
    - Dairy cow milk production values were updated for several states for 2020;
    - Slaughter data were revised for 2020.
- EPA revised annual milk fat values in the CEFM from 2000 through 2021 with updated annual values from USDA's Economic Research Services (ERS) dairy data (USDA 2022). In the previous *Inventory*, EPA derived annual averages from monthly ERS milk fat values, which is no longer available beyond 2010 (USDA 2021).
- EPA discovered and corrected an error within the CEFM related to the urinary energy input used for feedlot cattle, which affected VS results for this animal group. The urinary energy default was updated from 0.04 to 0.02 for feedlot cattle. These updates will affect values in Section 5.2 Manure Management.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. In addition to the documented approaches currently used to address data availability, EPA conducts the following annual assessments to identify and determine the applicability of newer data when updating the estimates to extend time series each year:

- Further research to improve the estimation of dry matter intake (as gross energy intake) using data from appropriate production systems;
- Updating input variables that are from older data sources, such as beef births by month, beef and dairy annual calving rates, and beef cow lactation rates;
- Investigating the availability of data for dairy births by month, to replace the current assumption that births are evenly distributed throughout the year;
- Investigating the availability of annual data for the DE, Y_m, and crude protein values of specific diet and feed components for grazing and feedlot animals (including investigating the availability of existing models to estimate diet characteristics, as well as the use and impact of feed additives on emissions);
- Further investigation on additional sources or methodologies for estimating DE for dairy cattle, given the many challenges in characterizing dairy cattle diets;
- Further evaluation of the assumptions about weights and weight gains for beef cows, such that trends beyond 2007 are updated, rather than held constant; and
- Further evaluation of the estimated weight for dairy cows (i.e., 1,500 lbs) that is based solely on Holstein cows as mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States.

Depending upon the outcome of ongoing investigations, future improvement efforts for enteric fermentation could include some of the following options which are additional to the regular updates, and may or may not have implications for regular updates once addressed:

- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses). Efforts to move to Tier 2 will consider the emissions significance of livestock types;
- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry;
- Comparison of the current CEFM with other models that estimate enteric fermentation emissions for quality assurance and verification;
- Investigation of recent research implications suggesting that certain parameters in enteric models may be simplified without significantly diminishing model accuracy; and
- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated. EPA plans to perform this uncertainty analysis following the completed updates to the CEFM.

EPA is continuously investigating these recommendations and potential improvements and working with USDA and other experts to utilize the best available data and methods for estimating emissions. Many of these improvements are major updates and may take multiple years to implement in full.

5.2 Manure Management (CRT Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions.[6] Methane is produced by the anaerobic decomposition of manure and nitrous oxide is produced from direct and indirect pathways through the processes of nitrification and denitrification; in addition, there are many underlying factors that can affect these resulting emissions from manure management, as described below.

When livestock manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO_2 and little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and animal type (particularly the different animal digestive systems), also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

As previously stated, N_2O emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the N in livestock dung

[6] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

and urine.[7] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure into the groundwater below, into riparian zones receiving drain or runoff water, or into the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure (manure includes both feces and urine), the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where organic N is mineralized or decomposed to NH_4 which is then nitrified to NO_3 (producing some N_2O as a byproduct) (nitrification). Next, the manure must be handled anaerobically where the nitrate is then denitrified to N_2O and N_2 (denitrification). NO_x can also be produced during denitrification (Groffman et al. 2000; Robertson and Groffman 2015). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS).

Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. However, storage systems are often designed to minimize leaching (e.g., clay soil or synthetic liners in lagoons). Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions from manure management in 2022 were 64.7 MMT CO_2 Eq. (2,312 kt); in 1990, emissions were 39.1 MMT CO_2 Eq. (1,398 kt). This represents a 65 percent increase in emissions from 1990. Emissions increased on average by 0.8 MMT CO_2 Eq. (2 percent) annually over this period. The majority of this increase is due to dairy cattle and beef cattle manure, where emissions increased 109 and 146 percent, respectively. From 2021 to 2022, there was a 3 percent decrease in total CH_4 emissions from manure management, mainly due to a decrease in swine, dairy, and beef cattle populations.

Although a large quantity of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy cattle and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system (IPCC 2006).

While national dairy animal populations have decreased since 1990, some states have seen increases in their dairy cattle populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus, the shift

[7] Direct and indirect N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (i.e., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the agricultural soil management source category within the Agriculture sector.

toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both the dairy cattle and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, 2002, 2007, 2012, and 2017 farm-size distribution data reported in the U.S. Department of Agriculture (USDA) *Census of Agriculture* (USDA 2019d).

In 2022, total N_2O emissions from manure management were estimated to be 17.0 MMT CO_2 Eq. (64 kt); in 1990, emissions were 13.4 MMT CO_2 Eq. (50 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have increased since 1990. Multiple drivers increase N_2O emissions, such as increasing nitrogen excretion rates for some animal types (see Annex, Table A-163) and increasing numbers of animals on feedlots versus other dry systems (e.g., pasture). Across the entire time series, the overall net effect is that N_2O emissions showed a 27 percent increase from 1990 to 2022, but recent declines in a few animal populations (e.g., swine and dairy cattle) resulted in a 0.9 percent decrease from 2021 to 2022.

Table 5-6 and Table 5-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.[8]

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Animal Type	1990	2005	2018	2019	2020	2021	2022
CH_4[a]	**39.1**	**55.0**	**67.7**	**66.7**	**66.9**	**66.4**	**64.7**
Dairy Cattle	16.0	26.4	35.7	34.4	34.7	34.3	33.4
Swine	17.4	22.7	24.7	24.9	24.9	24.6	23.8
Poultry	3.8	3.4	3.0	3.1	3.0	3.0	3.0
Beef Cattle	1.8	2.2	4.2	4.1	4.2	4.4	4.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**13.4**	**15.2**	**16.6**	**16.8**	**16.9**	**17.1**	**17.0**
Beef Cattle	5.2	6.0	5.9	6.0	6.1	6.4	6.4
Dairy Cattle	5.5	5.5	6.2	6.2	6.2	6.3	6.2
Swine	1.1	1.5	1.8	1.8	1.9	1.8	1.8
Poultry	1.3	1.8	2.3	2.3	2.3	2.3	2.3
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA
Total	**52.5**	**70.2**	**84.3**	**83.5**	**83.8**	**83.6**	**81.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

[8] Manure management emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory. See Annex 5 for more information on significance of estimated camel emissions.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the agricultural soils management category. Totals may not sum due to independent rounding.

Table 5-7: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2018	2019	2020	2021	2022
CH_4[a]	**1,398**	**1,964**	**2,418**	**2,382**	**2,390**	**2,373**	**2,312**
Dairy Cattle	572	943	1,274	1,227	1,238	1,226	1,193
Swine	621	812	882	890	888	877	851
Poultry	135	123	108	111	109	108	108
Beef Cattle	63	78	149	148	150	157	154
Horses	4	5	3	3	3	3	2
Sheep	3	2	2	2	2	2	2
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**50**	**57**	**63**	**63**	**64**	**65**	**64**
Beef Cattle	20	23	22	23	23	24	24
Dairy Cattle	21	21	23	23	24	24	23
Swine	4	6	7	7	7	7	7
Poultry	5	7	9	9	9	9	9
Sheep	+	1	1	1	1	1	1
Horses	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.5 kt.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the agricultural soils management category. Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type, including Tier 1, Tier 2, and use of the CEFM previously described for enteric fermentation. These methodologies use:

- IPCC (2019) Tier 1 default N_2O emission factors and MCFs for dry systems
- U.S. specific MCFs for liquid systems (ERG 2001)
- U.S. specific values for volatile solids (VS) production rate and nitrogen excretion rate for some animal types, including cattle values from the CEFM

This combination of Tier 1 and Tier 2 methods was applied to all livestock animal types and follows guidance for methodological choice presented in decision trees from the IPCC (2006). This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management.

See Annex 3.11 for more detailed information on the methodologies (including detailed formulas and emission factors), data used to calculate CH_4 and N_2O emissions, and emission results (including input variables and results at the state-level) from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of manure management CH_4 emissions for 1990 through 2022:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- VS production rate (by animal type and state or United States);
- Methane producing potential (B0) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2022 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from the USDA-NASS. For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 5.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017; horse and mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017; and American bison population for 2002, 2007, 2012, and 2017 were obtained from the *Census of Agriculture* (USDA 2019d). American bison population data for 1990 through 1999 were obtained from the National Bison Association (1999).
- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986; EPA 1992; Safley 2000; ERG 2003b; IPCC 2006; ERG 2010a). For a description of the TAM data used for cattle, see Annex 3.10.
- WMS usage was estimated for swine and dairy cattle for different farm size categories using state and regional data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2016c) and EPA (ERG 2000a; EPA 2002a and 2002b; ERG 2018, ERG 2019). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a; USDA APHIS 2000; UEP 1999, ERG 2023). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.
- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* (IPCC 2006). American bison VS production was assumed to be the same as NOF bulls.
- B_0 was determined for each animal type based on literature values (Morris 1976; Bryant et al. 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).
- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2019). The IPCC 2019 factors are more representative of U.S. systems and reflect the latest science. MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.

- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information available in the AgSTAR project database (EPA 2023). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).
- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) was multiplied by the B_0 (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions. See details in Step 5 of Annex 3.11.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect manure management N_2O emissions for 1990 through 2022:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volatilization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

Nitrous oxide emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex were assumed to be the same as NOF bulls.[9]
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006).
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture*

[9] Nex of American bison on grazing lands are accounted for and discussed in the agricultural soil management source category and included under pasture, range and paddock (PRP) emissions. Because American bison are maintained entirely on unmanaged WMS and N_2O emissions from unmanaged WMS are not included in the manure management source category, there are no N_2O emissions from American bison included in the manure management source category.

Operations (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves), the estimated amount of N excreted (kg per animal-year) that is managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year). See details in Step 6 of Annex 3.11.

Indirect N_2O emissions from volatilization (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{gas}$) divided by 100, the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions. See details in Step 6 of Annex 3.11.

Following these steps, direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year) for the years 1990 to 2022.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022. In some cases, the activity data source changed over the time series. For example, updated WMS distribution data were applied to 2016 for dairy cows and 2009 for swine. While previous WMS distribution data were from another data source, EPA integrated the more recent data source to reflect the best available current WMS distribution data for these animals. EPA assumed a linear interpolation distribution for years between the two data sources. Refer to Annex 3.11 for more details on data sources and methodology.

Uncertainty

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 *Inventory* (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. A normal probability distribution was assumed for all variables in the estimation equations. While there are plans to update the uncertainty to reflect recent manure management updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2022 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-8. Manure management CH_4 emissions in 2022 were estimated to be between 53.1 and 77.7 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2022 emission estimate of 64.7 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.3 and 21.1 MMT CO_2

Eq. (or approximately 16 percent below and 24 percent above the actual 2022 emission estimate of 17.0 MMT CO_2 Eq.).

A quantitative uncertainty analysis for this source category was also performed using the IPCC (2006) recommended Approach 1 based on simple error propagation as well. Based on this analysis, manure management:

- CH_4 emissions in 2022 were estimated to be between 50.4 and 79.0 MMT CO_2 Eq., which indicates a range of ±21 percent above and below the 2022 emission estimate of 64.7 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±30 percent default uncertainty factor for Tier 1 and ±20 percent default uncertainty factor for Tier 2 is applied to the emission factors (IPCC 2006).
- N_2O emissions in 2022 were estimated to be between 11.8 and 22.2 MMT CO_2 Eq., which indicates a range of ±31 percent above and below the 2022 emission estimate of 17.0 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±50 percent default uncertainty factor is applied to the emission factors (IPCC 2006).
- CH_4 and N_2O emissions in 2022 were estimated to be between 66.5 and 96.9 MMT CO_2 Eq., which indicates a range of ±19 percent above and below the 2022 emission estimate of 81.7 MMT CO_2 Eq. A ±25 percent uncertainty factor is applied to the activity data (e.g., animal populations), and a ±20-50 percent default uncertainty factor is applied to the emission factors (IPCC 2006).

Table 5-8: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	64.7	53.1	77.7	-18%	+20%
Manure Management	N_2O	17.0	14.3	21.1	-16%	+24%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. In addition, manure N data were checked by comparing state-level data with bottom-up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for N excreted, both for pasture and managed systems, and the sum of county estimates for the full time series. This was done to ensure consistency between excreted N within the manure management sector and those data provided to the managed soils sector. All errors identified were corrected.

Time-series data, including population, are validated by experts to ensure they are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_0, and MCF were also compared to the IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The

U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the IPCC (2006) default values.

For additional verification of the 1990 to 2022 estimates, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default IPCC (2006) values. Table 5-9 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC (2006) default emission factors. The U.S. implied emission factors fall within the range of the IPCC (2006) default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are less than the IPCC (2006) default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy cattle and swine across the time series. This increase reflects the dairy cattle and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions. See the Recalculations for explanations for changes that affect emissions which impact these implied emission factors.

Table 5-9: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH_4 from Manure Management (kg/head/year)

Animal Type	IPCC Default CH_4 Emission Factors (kg/head/year)[a]	1990	2005	2018	2019	2020	2021	2022
Dairy Cattle	48-112	29.3	53.0	67.0	65.0	65.9	65.0	64.1
Beef Cattle	1-2	0.8	0.9	1.8	1.8	1.8	1.9	1.9
Swine	10-45	11.5	13.3	12.0	11.6	11.5	11.8	11.6
Sheep	0.19-0.37	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Goats	0.13-0.26	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	0.02-1.4	0.1	0.1	0.05	0.05	0.05	0.05	0.05
Horses	1.56-3.13	1.9	1.4	1.2	1.2	1.2	1.2	1.2
American Bison	NA	0.8	0.9	0.9	0.9	0.9	0.9	0.9
Mules and Asses	0.76-1.14	0.4	0.4	0.4	0.4	0.4	0.4	0.4

NA (Not Applicable)

[a] Ranges reflect *2006 IPCC Guidelines* (Volume 4, Table 10.14) default emission factors for North America across different climate zones.

In addition, default IPCC (2006) emission factors for N_2O were compared to the U.S. *Inventory* implied N_2O emission factors. Default N_2O emission factors from the *2006 IPCC Guidelines* were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. *Inventory* values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

In the previous *Inventory*, 1990 to 2020 estimates were retained from the 1990 through 2020 *Inventory*, and 2021 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current *Inventory*, the calculations were rerun for all years, resulting in different estimates for 2021 than the prior *Inventory*.

There were also changes to emissions resulting from activity data changes, including:

- EPA updated the WMS distributions for broilers, layers, and beef feedlot animal types. For broilers, this affected 1993 through 2021, for layers 2000 through 2021, and for beef feedlots all years of the time series (ERG 2023).

- EPA updated the calf TAM values to coincide with values used within the CEFM. This affected all years of the time series.
- EPA updated the solid storage direct N_2O emission factor to the updated guidance provided in IPCC (2019).
- EPA updated how poultry digesters were applied, splitting other poultry and caged layers (previously done for broilers) as well as the year for which select swine anaerobic digesters were shutdown per notes provided in AgSTAR.
- EPA discovered and corrected an error within the CEFM (see NIR section 5.1 and annex 3.10) related to the urinary energy input used for feedlot cattle, which affected VS results for this animal group. The urinary energy default was updated from 0.04 to 0.02 for feedlot cattle.

The cumulative effect of all these recalculations had a minor impact on the overall manure management emissions estimates:

- CH_4 emissions increased an average 0.6 percent over the time series, with the largest decrease of 0.2 percent (0.1 MMT CO_2 Eq) in 2002 to the largest increase of 1.8 percent (1.2 MMT CO_2 Eq.) in 2017.
- N_2O emissions increased an average 3.4 percent over the time series, with the largest decrease of 3.6 percent (0.6 MMT CO_2 Eq.) in 2020 and the largest increase of 7.8 percent (1.0 MMT CO_2 Eq.) in 1990.
- Over the time series the average total emissions increased by 1.2 percent from the previous *Inventory*. The changes ranged from the largest decrease 0.5 percent (0.4 MMT CO_2 Eq.) in 2020, to the largest increase 2.1 percent (1.1 MMT CO_2 Eq.) in 1990.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. In addition to the documented approaches currently used to address data availability, EPA conducts data assessments to pursue a number of potential improvements.

Potential improvements (long-term improvements) for future *Inventory* years include:

- Providing supplemental details on CH_4 emissions reductions due to the use of anaerobic digesters (the *Inventory* currently estimates only emissions from anaerobic digestion systems).
- Investigating the updated IPCC *2019 Refinement* default N_2O emissions factor for anaerobic digesters. Historically, EPA has not estimated N_2O emissions from digesters as the default guidance was no emissions. Incorporating AgSTAR data for N_2O emissions, like CH_4 emissions, is a longer-term goal for EPA.
- Investigating updates to the current anaerobic digester MCFs based on IPCC (2019).

EPA is aware of the following potential updates or improvements but notes that implementation will be based on available resources and data availability:

- Updating the B_0 data used in the *Inventory*, as data become available. EPA is conducting outreach with counterparts from USDA as to available data and research on B_0.
- Comparing CH_4 and N_2O emission estimates with estimates from other models and more recent studies and compare the results to the *Inventory*.
- Comparing manure management emission estimates with on-farm measurement data to identify opportunities for improved estimates.
- Comparing VS and Nex data to literature data to identify opportunities for improved estimates.

- Determining if there are revisions to the U.S.-specific method for calculating liquid systems for MCFs based on updated guidance from the IPCC *2019 Refinement*. EPA previously began this investigation to determine the potential differences between the methods.
- Investigating improved emissions estimate methodologies for swine pit systems with less than one month of storage (the updated swine WMS data included this WMS category).
- Improving the linkages with the Enteric Fermentation source category estimates. For future Inventories, it may be beneficial to have the CEFM and Manure Management calculations in the same model, as they rely on much of the same activity data and on each other's outputs to properly calculate emissions. EPA has begun this investigation and plans to develop a model to calculate emissions for these two categories.
- Continuing to investigate new sources of WMS data. EPA is collaborating with the USDA to collect or use existing survey data for potential improvements to the *Inventory*.
- Revising the uncertainty analysis to address changes that have been implemented to the CH_4 and N_2O estimates. The plan is to align the timing of the updated Manure Management uncertainty analysis with the uncertainty analysis for Enteric Fermentation.

5.3 Rice Cultivation (CRT Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013) that create anaerobic conditions leading to CH_4 production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH_4 produced by methanogenic bacteria in flooded rice fields is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH_4 into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water (van Bodegom et al. 2001).

Water management is arguably the most important factor affecting CH_4 emissions in rice cultivation, and improved water management has the largest potential to mitigate emissions (Yan et al. 2009). Upland rice fields are not flooded, and therefore do not produce CH_4, but large amounts of CH_4 can be emitted in continuously irrigated fields, which is the most common practice in the United States (USDA 2012). Single or multiple aeration events with drainage of a field during the growing season can significantly reduce these emissions (Wassmann et al. 2000a), but drainage may also increase N_2O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have fewer living stems reaching the soil, thus reducing the amount of CH_4 transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH_4 emissions from flooded rice fields including rice residue straw management and application of organic amendments, in addition to cultivar selection due to differences in the amount of root exudates[10] among rice varieties (Neue et al. 1997). These practices influence the amount of organic matter available for methanogenesis, and some practices, such as mulching rice straw or composting organic amendments, can reduce the amount of labile carbon and limit CH_4 emissions (Wassmann et al. 2000b).

[10] The roots of rice plants add organic material to the soil through a process called "root exudation." Root exudation is thought to enhance decomposition of the soil organic matter and release nutrients that the plant can absorb for production. The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Fertilization practices also influence CH_4 emissions, particularly the use of fertilizers with sulfate, which can reduce CH_4 emissions (Wassmann et al. 2000b; Linquist et al. 2012). Other environmental variables also impact the methanogenesis process such as soil temperature and soil type. Soil temperature regulates the activity of methanogenic bacteria, which in turn affects the rate of CH_4 production. Soil texture influences decomposition of soil organic matter but is also thought to have an impact on oxidation of CH_4 in the soil (Sass et al. 1994).

Rice is currently cultivated in 12 states, including Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, Tennessee, and Texas. Soil types, rice varieties, and cultivation practices vary across the United States, but most farmers apply fertilizers and do not harvest crop residues. In addition, a second, ratoon rice crop is sometimes grown in the Southeastern region of the country. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Methane emissions from ratoon crops are higher than those from the primary crops due to the increased amount of labile organic matter available for anaerobic decomposition in the form of relatively fresh crop residue straw. Emissions tend to be higher in rice fields if the residues have been in the field for less than 30 days before planting the next rice crop (Lindau and Bollich 1993; IPCC 2006; Wang et al. 2013).

A combination of Tier 1 and 3 methods are used to estimate CH_4 emissions from rice cultivation across most of the time series, while a surrogate data method has been applied to estimate national emissions for 2021 to 2022 in this *Inventory* due to lack of data in these years of the time series. National emission estimates based on surrogate data will be recalculated in a future *Inventory* with the Tier 1 and 3 methods as data becomes available.

Overall, rice cultivation is a minor source of CH_4 emissions in the United States relative to other source categories (see Table 5-10, Table 5-11, and Figure 5-3). Most emissions occur in Arkansas, California, Louisiana, Mississippi, Missouri, and Texas. In 2022, CH_4 emissions from rice cultivation were 18.9 MMT CO_2 Eq. (674 kt CH_4). Annual emissions fluctuated between 1990 and 2022, which is largely due to differences in the amount of rice harvested areas over time. There has been a marginal decrease in emissions since 1990. Interestingly, the estimated emissions in 2022 are roughly the same as emissions in 1990.

Table 5-10: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990	2005	2018	2019	2020	2021	2022
Arkansas	6.3	8.8	8.0	5.6	6.8	NE	NE
California	3.2	3.4	3.7	3.5	3.6	NE	NE
Florida	+	+	+	+	+	NE	NE
Illinois	+	+	+	+	+	NE	NE
Kentucky	+	+	+	+	+	NE	NE
Louisiana	3.5	3.8	3.7	3.2	3.7	NE	NE
Minnesota	+	+	+	+	+	NE	NE
Mississippi	1.1	1.3	0.7	0.6	0.6	NE	NE
Missouri	0.5	1.2	1.2	0.9	1.0	NE	NE
New York	+	+	+	+	+	NE	NE
Tennessee	+	+	+	+	+	NE	NE
Texas	4.3	1.9	2.6	1.9	2.9	NE	NE
Total	**18.9**	**20.6**	**19.9**	**15.6**	**18.6**	**18.3**	**18.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

NE (Not Estimated). State-level emissions are not estimated for 2021 through 2022 in this *Inventory*. A surrogate method is used to estimate emissions for these years only at the national scale.

Note: Totals may not sum due to independent rounding.

Table 5-11: CH_4 Emissions from Rice Cultivation (kt CH_4)

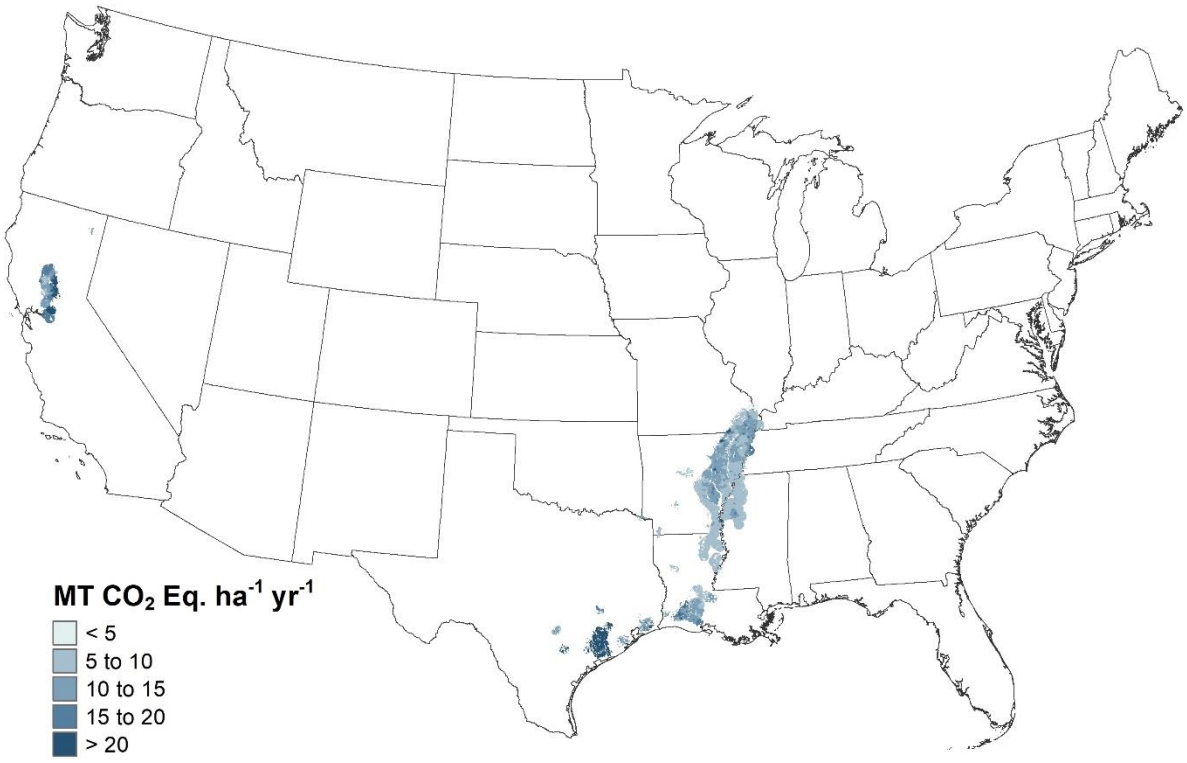
State	1990	2005	2018	2019	2020	2021	2022
Arkansas	224.2	315.5	287.1	200.5	243.4	NE	NE
California	114.5	122.8	131.5	123.9	129.1	NE	NE
Florida	+	1.2	+	+	+	NE	NE
Illinois	+	0.4	0.1	+	0.1	NE	NE
Kentucky	+	+	+	+	+	NE	NE
Louisiana	124.9	135.0	131.4	113.7	130.4	NE	NE
Minnesota	1.0	1.7	+	0.8	+	NE	NE
Mississippi	39.0	46.5	24.3	20.3	21.5	NE	NE
Missouri	19.5	42.7	43.0	31.8	34.4	NE	NE
New York	0.2	+	+	+	+	NE	NE
Tennessee	+	0.1	+	+	+	NE	NE
Texas	153.5	69.5	93.6	67.0	104.7	NE	NE
Total	**677**	**735**	**711**	**558**	**664**	**653**	**674**

+ Does not exceed 0.5 kt.

NE (Not Estimated). State-level emissions are not estimated for 2021 through 2022 in this *Inventory*. A surrogate method is used to estimate emissions for these years only at the national scale.

Note: Totals may not sum due to independent rounding.

Figure 5-3: Annual CH_4 Emissions from Rice Cultivation, 2020, Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2021 and 2022 in this *Inventory* using a surrogate data method described in the Methodology section; therefore, the fine-scale emission patterns in this map are based on the estimates for 2020.

Methodology and Time-Series Consistency

The methodology used to estimate CH_4 emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes the DayCent process-based model to estimate CH_4 emissions from rice cultivation (Cheng et al. 2013) and has been tested in the United States (see Annex 3.12) and Asia (Cheng et al. 2013, 2014). The model simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH_4, as well as CH_4 transport through the plant and via ebullition (Cheng et al. 2013). The method captures the influence of organic amendments and rice straw management on methanogenesis in the flooded soils, and ratooning of rice crops with a second harvest during the growing season. In addition to CH_4 emissions, DayCent simulates soil carbon stock changes and N_2O emissions (Parton et al. 1987 and 1998; Del Grosso et al. 2010) and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops.

The Tier 1 method is applied to estimate CH_4 emissions from rice when grown in rotation with crops that are not simulated by DayCent, such as vegetable crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH_4 emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). The Tier 3 method using DayCent has not been fully tested for estimating emissions associated with these conditions.

The Tier 1 method for estimating CH_4 emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission rate represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust the base emission rate for water management and organic amendments that differ from continuous flooding with no organic amendments. The method accounts for pre-season and growing season flooding; types and amounts of organic amendments; and the number of rice production seasons within a single year (i.e., single cropping and double-cropping with ratooning). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[11]

Rice cultivation areas are based on crop and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021, Johnson and Mueller 2010). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (See Section 6.1, Representation of the U.S. Land Base for more information).

The NRI is a statistically based sample of all non-federal land and includes approximately 604,000 survey locations in agricultural cropland and grassland for the conterminous United States and Hawaii of which 7,888 include one or more years of rice cultivation. The Tier 3 method is used to estimate CH_4 emissions from 5,998 of the NRI survey locations, and the remaining 1,890 survey locations are estimated with the Tier 1 method. Each NRI survey location is associated with a survey weight that allows scaling of CH_4 emission to the entire land base with rice cultivation (i.e., each weight approximates the amount of area with the same land-use/management history as the survey location). Land-use and some management information in the NRI (e.g., crop type, soil attributes, and irrigation) were collected on a 5-year cycle beginning in 1982, along with cropping rotation data in four out of five years for each five-year time period (i.e., 1979 to 1982, 1984 to 1987, 1989 to 1992, and 1994 to 1997). The NRI program began collecting annual data in 1998, with data through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021). CDL data have a 30 to 58 m spatial resolution, depending on the year. NRI survey locations are overlaid on the CDL in a geographic information

[11] See http://www.nrel.colostate.edu/projects/ALUsoftware/.

system, and the crop types are extracted to extend the cropping histories. The harvested rice areas in each state are presented in Table 5-12.

Table 5-12: Rice Area Harvested (1,000 Hectares)

State/Crop	1990	2005	2018	2019	2020	2021	2022
Arkansas	611	782	659	512	663	NE	NE
California	251	237	226	218	224	NE	NE
Florida	0	3	0	0	0	NE	NE
Illinois	0	1	0	0	1	NE	NE
Kentucky	0	0	0	0	0	NE	NE
Louisiana	399	400	356	313	383	NE	NE
Minnesota	3	6	0	3	0	NE	NE
Mississippi	177	191	98	96	109	NE	NE
Missouri	48	96	99	74	85	NE	NE
New York	1	0	0	0	0	NE	NE
Tennessee	0	1	0	0	0	NE	NE
Texas	294	104	164	119	167	NE	NE
Total	**1,784**	**1,823**	**1,603**	**1,335**	**1,633**	**NE**	**NE**

NE (Not Estimated). Area data will be updated in the next *Inventory*.
Note: Totals may not sum due to independent rounding.

The Southeastern states have sufficient growing periods for a ratoon crop in some years (Table 5-13). For example, the growing season length is occasionally sufficient for ratoon crops to be grown on about two percent of the rice fields in Arkansas. No data are available about ratoon crops in Missouri or Mississippi, so the average amount of ratooning in Arkansas was assigned to these states. Ratoon cropping occurs much more frequently in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2015), averaging 32 percent and 45 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (49 percent). Ratoon rice crops are not grown in California. Ratooning practices are assigned to individual NRI locations using a hot-deck imputation method with six complete imputations for each NRI location to address uncertainty. The method is based on random assignment of ratooning to approximate the percentages of fields managed with ratooning provided in Table 5-14.

Table 5-13: Average Ratooned Area as Percent of Primary Growth Area (Percent)

State	1990-2015
Arkansas[a]	1.9%
California	0%
Florida[b]	45.2%
Louisiana[c]	39.5%
Mississippi[a]	37.8%
Missouri[a]	2.4%
Texas[d]	49.5%

[a] Arkansas: *1990–2000* (Slaton 1999 through 2001); *2001–2011* (Wilson 2002 through 2007, 2009 through 2012); *2012–2013* (Hardke 2013, 2014). Estimates of ratooning for Missouri and Mississippi are based on the data from Arkansas.
[b] Florida - Ratoon: *1990–2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002–2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004 through 2005); *2005–2013* (Gonzalez 2007 through 2014).
[c] Louisiana: *1990–2013* (Linscombe 1999, 2001 through 2014).
[d] Texas: *1990–2002* (Klosterboer 1997, 1999 through 2003); *2003–2004* (Stansel 2004 through 2005); *2005* (Texas Agricultural Experiment Station 2006); *2006–2013* (Texas Agricultural Experiment Station 2007 through 2014).

While rice crop production in the United States includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding was assumed in the DayCent simulations and the Tier 1 analysis. Variation in flooding can be incorporated in future inventories if updated water management data are available.

Winter flooding is another key practice associated with water management in rice fields, and the impact of winter flooding on CH_4 emissions is addressed in the Tier 3 and Tier 1 analyses. Flooding is used to prepare fields for the next growing season, and to create waterfowl habitat (Young 2013; Miller et al. 2010; Fleskes et al. 2005). Fitzgerald et al. (2000) suggests that as much as 50 percent of the annual emissions may occur during winter flooding. Winter flooding is a common practice with an average of 34 percent of fields managed with winter flooding in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields managed with winter flooding in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of flooding is assumed to be relatively constant over the *Inventory* time series. Similar to ratooning practices, winter flooding is assigned to individual NRI locations using a hot-deck imputation method with six complete imputations for each NRI location to address uncertainty. The method is based on random assignment of winter flooding to approximate the percentages of fields managed with winter flooding as discussed above.

A data splicing method is used to estimate emissions from 2021 to 2022 associated with the rice CH_4 emissions for Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving average (ARMA) errors was used to estimate the relationship between the surrogate data and emissions data from 1990 through 2020, which were derived using the Tier 3 methods (Brockwell and Davis 2016). Surrogate data are based on rice commodity statistics from USDA-NASS.[12] See Box 5-2 for more information about the surrogate data method. For the Tier 1 method, a linear-time series model is used to estimate emissions for 2021 to 2022 without surrogate data.

Box 5-2: Surrogate Data Method

An approach to extend the time series is needed to estimate emissions from rice cultivation because there are gaps in activity data at the end of the time series. This is mainly because the National Resources Inventory (NRI) does not release data every year, and the NRI is a key data source for estimating greenhouse gas emissions.

A surrogate data method has been selected to impute missing emissions at the end of the time series. A linear regression model with autoregressive moving average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the observed 1990 to 2020 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., CH_4 emissions), $X\beta$ is the surrogate data that is used to predict the missing emissions data, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the observed data for 1990 to 2020 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2021 to 2022.

A critical issue in using splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. For example, predicting CH_4 emissions will increase the total variation in the emission estimates for these specific years, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2020).

[12] See https://quickstats.nass.usda.gov/.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and data splicing methods are used to approximate emissions for the remainder of the 2021 to 2022 time series based on the emissions data from 1990 to 2020. The surrogate data method and linear time series approach, used for the Tier 3 and 1 methods, respectively, are consistent with data splicing methods in IPCC (2006).

Uncertainty

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For the first variance component, a Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods for the management data, as well as emission factors and model structure/parameterization, respectively. The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire area of rice cultivation, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method (See Box 5-2 for information about propagating uncertainty with the surrogate data method). The uncertainties from the Tier 1 and 3 approaches are combined to produce the final CH_4 emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12.

Rice cultivation CH_4 emissions in 2022 were estimated to be between 5.1 and 32.6 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 73 percent below to 73 percent above the 2022 emission estimate of 18.9 MMT CO_2 Eq. (see Table 5-14).

Table 5-14: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Inventory Method	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	Tier 3	CH_4	15.9	2.2	29.6	-86%	+86%
Rice Cultivation	Tier 1	CH_4	3.0	2.0	4.0	-34%	+34%
Rice Cultivation	**Total**	**CH_4**	**18.9**	**5.1**	**32.6**	**-73%**	**+73%**

[a] Range of emission estimates is the 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures include checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Model results are compared to field measurements to verify that results adequately represent CH_4 emissions. The comparisons included over 17 long-term experiments, representing about 238 combinations of management treatments across all the sites. A statistical relationship was developed to assess uncertainties in the model structure and parameterization, adjusting the estimates for model bias and assessing precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations, including a) updated time series of land representation data that identifies which points and years were sown with rice (Nelson et al 2020), b) extending the time-series of crop history with CDL data, c) imputing ratooning and winter flooding onto individual NRI survey points, d) updated fertilizer and organic amendment additions, and e) revisions to the approach for assigning organic matter amendments and crop residue inputs. As a result of these changes, CO_2-equivalent emissions changed annually with an average annual increase of 0.97 MMT CO_2 Eq., or 5.5 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key planned improvement for rice cultivation is to refine the model algorithms and re-calibration of the Tier 3 DayCent model using the latest observational data from experiments. Another improvement is collection of more information about water management and refinement of the application to incorporate mid-season drainage and alternate wetting and drying systems. Improvements are expected to be completed for the next *Inventory* (i.e., 2025 submission to the UNFCCC, 1990 through 2023 *Inventory*), pending prioritization of resources.

5.4 Agricultural Soil Management (CRT Source Category 3D)

Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989).[13] Mineral nitrogen is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of nitrogen from the atmosphere.[14] Several agricultural activities increase mineral nitrogen availability in soils that lead to direct N_2O emissions at the site of a management activity (see Figure 5-4) (Mosier et al. 1998). These activities include synthetic nitrogen fertilization; application of managed livestock manure; application of other organic materials such as biosolids (i.e., treated sewage sludge); deposition of manure on soils by domesticated animals in pastures, range, and paddocks (PRP) (i.e., unmanaged manure); retention of crop residues (nitrogen-fixing legumes and non-legume crops and forages); and drainage of organic soils[15] (i.e., Histosols) (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, cover crops, and fallowing of land, can influence nitrogen mineralization from soil organic matter and levels of asymbiotic nitrogen fixation. Indirect emissions of N_2O occur when nitrogen is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized nitrogen, and (2) surface runoff and leaching of applied/mineralized nitrogen

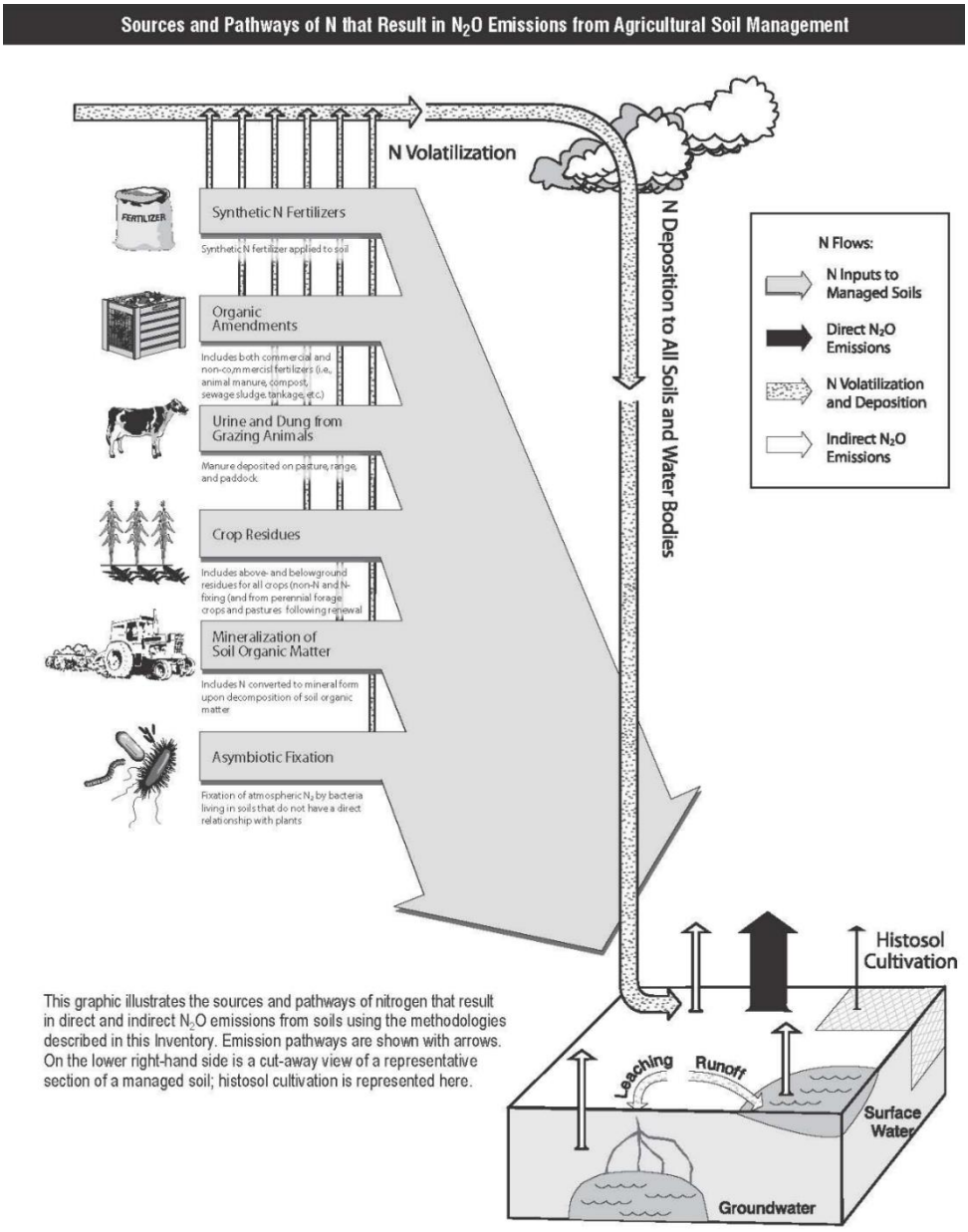
[13] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of nitrification and denitrification.

[14] Asymbiotic nitrogen fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[15] Drainage of organic soils in former wetlands enhances mineralization of nitrogen-rich organic matter, thereby increasing N_2O emissions from these soils.

into groundwater and surface water.[16] Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Section 6.1). Nitrous oxide emissions from forest land and settlements soils are found in Sections 6.2 and 6.10, respectively.

Figure 5-4: Sources and Pathways of Nitrogen that Result in N_2O Emissions from Agricultural Soil Management



[16] These processes entail volatilization of applied or mineralized nitrogen as NH_3 and NO_x, transformation of these gases in the atmosphere (or upon deposition), and deposition of the nitrogen primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x. In addition, hydrological processes lead to leaching and runoff of NO_3^- that is converted to N_2O in aquatic systems, e.g., wetlands, rivers, streams and lakes. Note: N_2O emissions are not estimated for aquatic systems associated with nitrogen inputs from terrestrial systems in order to avoid double-counting.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions in 2022 are 290.8 MMT CO_2 Eq. (1,097 kt) (see Table 5-15 and Table 5-16). Annual N_2O emissions from agricultural soils are 3.2 percent greater in 2022 compared to 1990, but emissions fluctuated between 1990 and 2022 due to inter-annual variability largely associated with weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2022, cropland accounted for 68 percent of total direct emissions on average from agricultural soil management, while grassland accounted for 32 percent. On average, 79 percent of indirect emissions are from croplands and 21 percent from grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-17 and Table 5-18.

Table 5-15: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Direct	**258.8**	**265.6**	**298.3**	**280.9**	**262.8**	**267.7**	**262.5**
Cropland	174.9	180.6	208.9	193.4	182.4	184.3	180.3
Grassland	83.9	85.1	89.4	87.5	80.3	83.4	82.1
Indirect	**29.9**	**28.4**	**35.1**	**34.7**	**29.4**	**30.3**	**28.3**
Cropland	23.6	22.3	28.1	28.0	23.3	24.1	22.2
Grassland	6.4	6.1	7.0	6.8	6.1	6.2	6.1
Total	**288.8**	**294.1**	**333.4**	**315.6**	**292.1**	**298.0**	**290.8**

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-16: N_2O Emissions from Agricultural Soils (kt N_2O)

Activity	1990	2005	2018	2019	2020	2021	2022
Direct	**977**	**1,002**	**1,126**	**1,060**	**992**	**1,010**	**990**
Cropland	660.0	681.4	788.3	729.9	688.5	695.4	680.6
Grassland	316.7	321.1	337.4	330.0	303.1	314.6	309.9
Indirect	**113**	**107**	**133**	**131**	**111**	**114**	**107**
Cropland	89.0	84.2	106.2	105.6	88.0	91.1	83.9
Grassland	24.0	23.1	26.4	25.5	22.9	23.3	22.9
Total	**1,090**	**1,110**	**1,258**	**1,191**	**1,102**	**1,124**	**1,097**

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and Nitrogen Input Type (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Cropland	**174.9**	**180.6**	**208.9**	**193.4**	**182.4**	**184.3**	**180.3**
Mineral Soils	**171.5**	**177.3**	**205.9**	**190.5**	**179.5**	**181.4**	**177.4**
Synthetic Fertilizer	61.0	64.3	70.3	65.7	63.2	63.4	62.0
Organic Amendment[a]	11.5	12.7	14.7	14.6	14.4	14.7	14.6
Residue N[b]	34.1	35.0	39.6	34.5	37.6	33.2	32.4
Mineralization and Asymbiotic Fixation	64.8	65.3	81.3	75.7	64.3	70.1	68.4
Drained Organic Soils	3.4	3.2	3.0	2.9	2.9	2.9	2.9
Grassland	**83.9**	**85.1**	**89.4**	**87.5**	**80.3**	**83.4**	**82.1**
Mineral Soils	**81.6**	**82.8**	**87.2**	**85.2**	**78.1**	**81.1**	**79.8**
Synthetic Fertilizer	+	+	+	+	+	+	+
PRP Manure	15.4	14.2	14.0	13.6	13.3	13.9	13.8
Managed Manure[c]	+	+	+	+	+	+	+

Biosolids (i.e., treated Sewage Sludge)	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Residue N[d]	27.1	28.4	28.0	28.3	28.2	26.3	25.9
Mineralization and Asymbiotic Fixation	38.9	39.8	44.8	42.9	36.2	40.5	39.8
Drained Organic Soils	2.3	2.2	2.2	2.2	2.2	2.3	2.3
Total	**258.8**	**265.6**	**298.3**	**280.9**	**262.8**	**267.7**	**262.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Organic amendment inputs include managed manure, daily spread manure, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).

[b] Cropland residue nitrogen inputs include nitrogen in unharvested cover crops as well as harvested crops.

[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.

[d] Grassland residue nitrogen inputs include residual biomass, both legumes and grasses, that is ungrazed and becomes dead organic matter.

Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Table 5-18: Indirect N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
Cropland	**23.6**	**22.3**	**28.1**	**28.0**	**23.3**	**24.1**	**22.2**
Volatilization & Atm. Deposition	6.6	7.0	7.9	7.1	7.5	7.4	7.3
Surface Leaching & Run-Off	17.0	15.3	20.3	20.9	15.8	16.7	14.9
Grassland	**6.4**	**6.1**	**7.0**	**6.8**	**6.1**	**6.2**	**6.1**
Volatilization & Atm. Deposition	3.4	3.4	3.3	3.2	3.0	3.1	3.2
Surface Leaching & Run-Off	2.9	2.7	3.7	3.6	3.1	3.0	2.9
Total	**29.9**	**28.4**	**35.1**	**34.7**	**29.4**	**30.3**	**28.3**

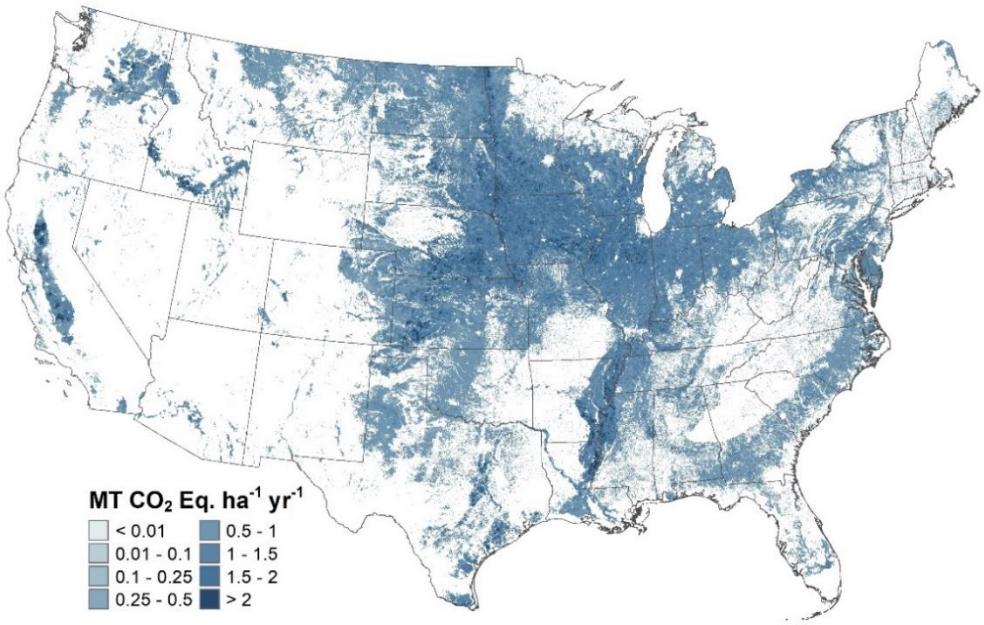
Notes: Estimates for 2021 to 2022 are based on a data splicing method, except for other organic nitrogen amendments that are based on a data splicing method for 2018 to 2022 (see Methodology section). Totals may not sum due to independent rounding.

Figure 5-5 and Figure 5-6 show regional patterns for direct N_2O emissions. Figure 5-7 and Figure 5-8 show indirect N_2O emissions from volatilization, and Figure 5-9 and Figure 5-10 show the indirect N_2O emissions from leaching and runoff in croplands and grasslands, respectively.

Direct N_2O emissions from croplands occur throughout all of the cropland regions but tend to be high in the Midwestern Corn Belt Region (particularly, Illinois, Iowa, Kansas, Minnesota, Nebraska), where a large portion of the land is used for growing highly fertilized corn and nitrogen-fixing soybean crops (see Figure 5-5). There are high emissions from the Southeastern region, and portions of the Great Plains. Emissions are also high in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado and Wyoming through Nebraska, Snake River Valley in Idaho, and the Central Valley in California. Direct emissions from croplands are low in mountainous regions of the Eastern United States because only a small portion of land is cultivated, and in much of the Western United States where rainfall and access to irrigation water are limited, in addition to mountainous, which are generally not suitable for crop production.

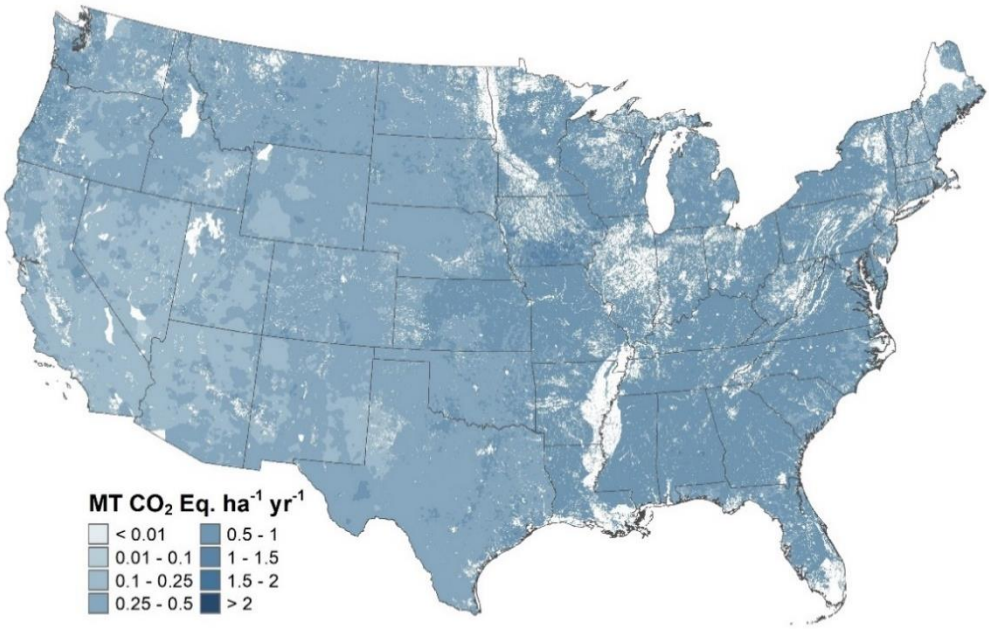
Direct N_2O emissions from grasslands are more evenly distributed throughout the United States compared to emissions from cropland due to suitable areas for grazing in most regions (see Figure 5-6). Total emissions tend be highest in the Great Plains and western United States where a large proportion of the land is dominated by grasslands with cattle and sheep grazing (particularly Kansas, Montana, Nebraska, New Mexico, Oklahoma, South Dakota, Texas).

Figure 5-5: Croplands, 2020 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-6: Grasslands, 2020 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model

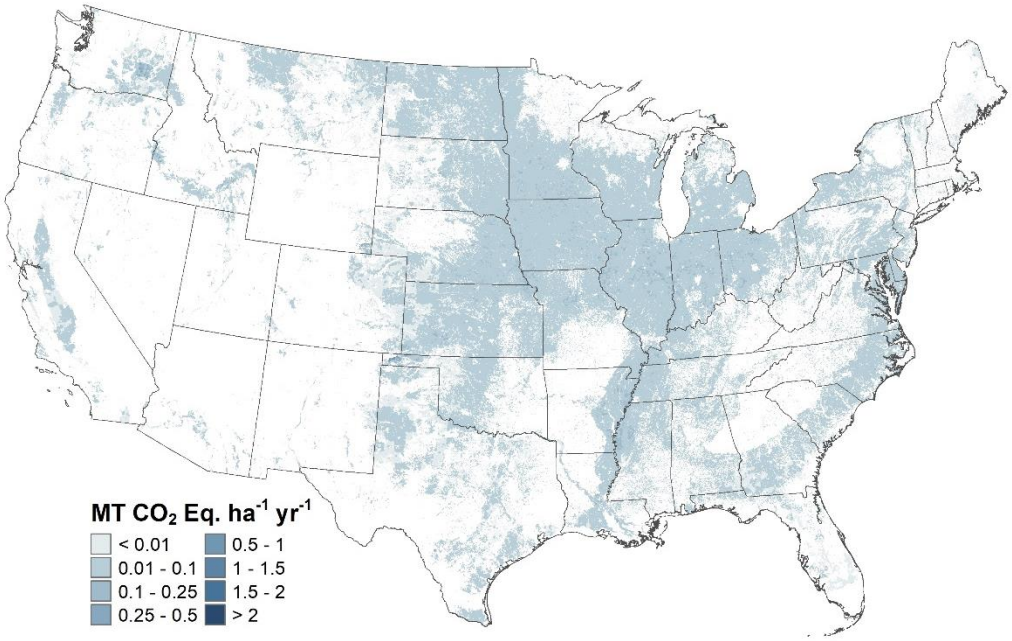


Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Indirect N_2O emissions from volatilization in croplands have a similar pattern as the direct N_2O emissions with higher emissions in the Midwestern Corn Belt, Lower Mississippi River Basin, Southeastern region, and parts of the Great Plains and irrigated areas of the Western United States. Indirect N_2O emissions from volatilization in grasslands are higher in the Eastern and Central United States, along with relatively small areas scattered around the Western United States. The higher emissions are partly due to large additions of PRP manure nitrogen, which in turn, stimulates NH_3 volatilization.

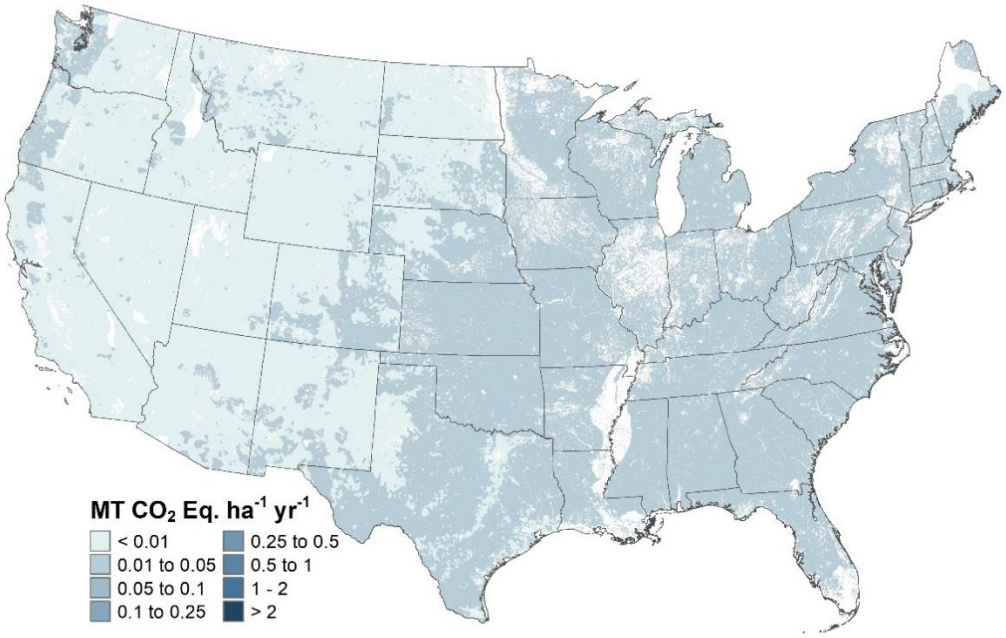
Indirect N_2O emissions from surface runoff and leaching of applied/mineralized nitrogen in croplands is highest in the Midwestern Corn Belt. There are also relatively high emissions associated with nitrogen management in the Lower Mississippi River Basin, Piedmont region of the Southeastern United States and the Mid-Atlantic states. In addition, areas of high emissions occur in portions of the Great Plains that have irrigated croplands with high leaching rates of applied/mineralized nitrogen. Indirect N_2O emissions from surface runoff and leaching of applied/mineralized nitrogen in grasslands are higher in the eastern United States and coastal Northwest region. These regions have greater precipitation and higher levels of leaching and runoff compared to arid to semi-arid regions in the Western United States.

Figure 5-7: Croplands, 2020 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model



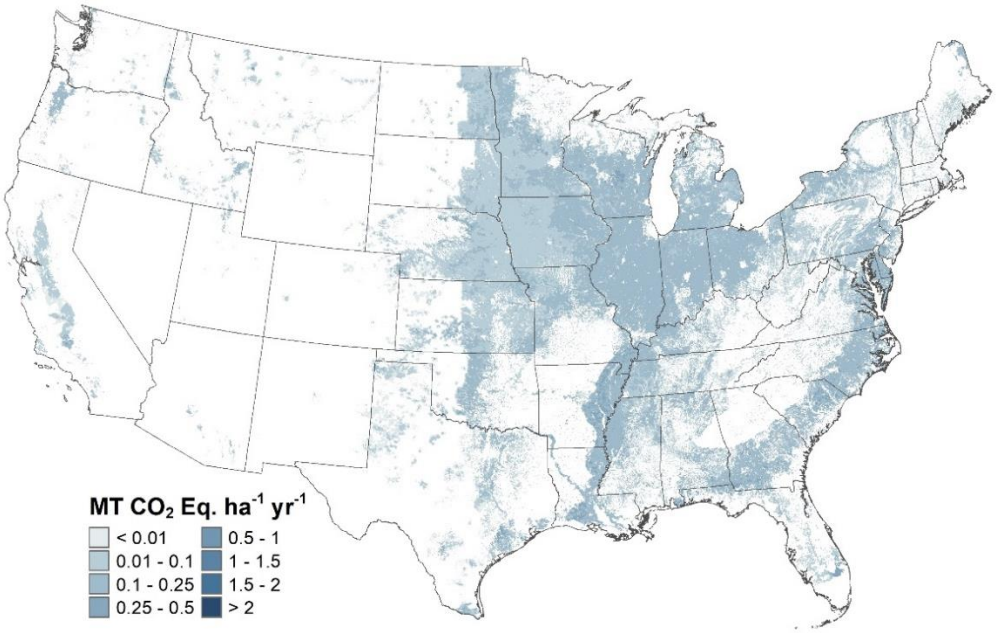
Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-8: Grasslands, 2020 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model



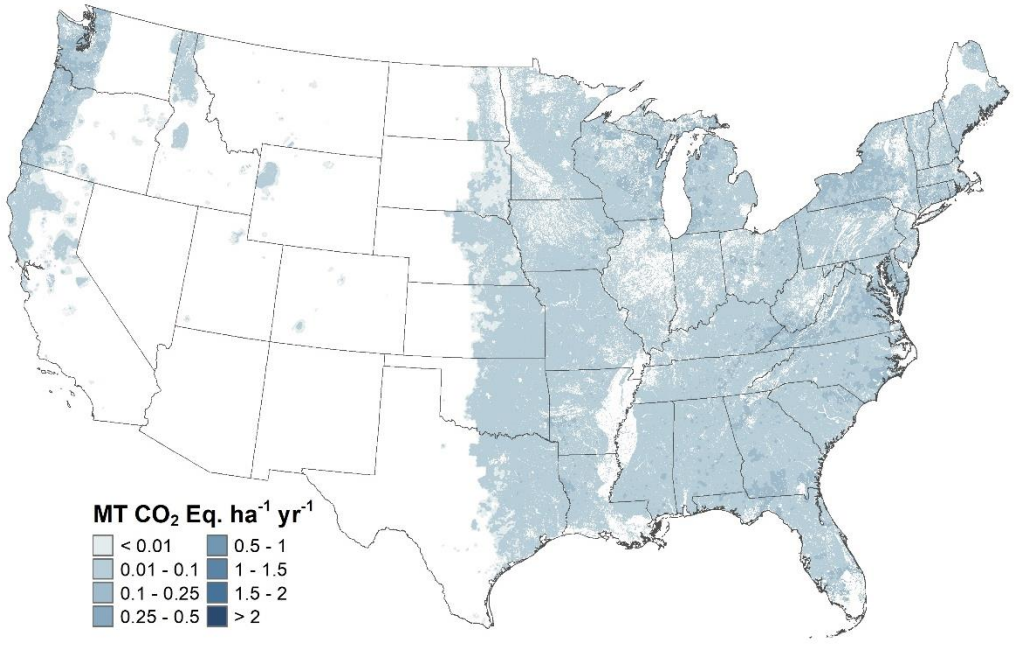
Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-9: Croplands, 2020 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 5-10: Grasslands, 2020 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2022 using a splicing method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Methodology and Time-Series Consistency

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the agricultural soil management source category into five components, including (1) direct emissions from nitrogen additions to cropland and grassland mineral soils from synthetic fertilizers, biosolids (i.e., treated sewage sludge), crop residues (legume nitrogen-fixing and non-legume crops), and organic amendments; (2) direct emissions from soil organic matter mineralization due to land use and management change; (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from nitrogen additions and manure deposition to soils that lead to volatilization, leaching, or runoff of nitrogen and subsequent conversion to N_2O.

In this source category, the United States reports on all croplands, as well as all managed grasslands, whereby anthropogenic greenhouse gas emissions are estimated in a manner consistent with the managed land concept (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation[17] and mineralization of nitrogen associated with decomposition of soil organic matter and residues. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

In addition, estimates of N_2O emissions from managed croplands and grasslands are not available for Alaska and Hawaii except for managed manure and PRP nitrogen, and biosolid additions for Alaska, and managed manure and

[17] Nitrogen inputs from asymbiotic nitrogen fixation are not directly addressed in *2006 IPCC Guidelines* but are a component of the nitrogen inputs and total emissions from managed lands and are included in the Tier 3 approach developed for this source.

PRP nitrogen, biosolids additions, and crop residue for Hawaii. There is a planned improvement to include the additional sources of emissions in a future *Inventory*.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches, along with application of a splicing method for latter years in the *Inventory* time series (IPCC 2006; Del Grosso et al. 2010). A Tier 3 process-based model (DayCent) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, as well as the direct emissions from non-federal grasslands except for applications of biosolids (i.e., treated sewage sludge) (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-3 for further elaboration). Moreover, the Tier 3 approach addresses direct N_2O emissions and soil carbon stock changes from mineral cropland soils in a single analysis. Carbon and nitrogen dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil carbon and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are considered between carbon and nitrogen cycling in soils.

Crop and land use histories are based on the USDA National Resources Inventory (NRI) (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021; Johnson and Mueller 2010). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1).

The NRI is a statistically-based sample and includes 364,333 survey locations on agricultural land for the conterminous United States that are included in the Tier 3 method. The Tier 1 approach is used to estimate the emissions from an annual average of 239,757 locations in the NRI survey across the time series, which are designated as cropland or grassland (discussed later in this section). The Tier 1 method is used to estimate emissions for components that are not simulated by DayCent. DayCent has not been parametrized to simulate some crop types and soil types, as described below. Each survey location is associated with a survey weight that allows scaling of N_2O emissions from NRI survey locations to the entire country (i.e., each survey weight is an approximation of the amount of area with the same land-use/management history as the survey location). Each NRI survey location was sampled on a 5-year cycle from 1982 until 1997. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, which are currently available through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021). CDL data have a 30 to 58 m spatial resolution, depending on the year. Specifically, NRI survey locations are overlaid on the CDL in a geographic information system, and the crop types are extracted to extend the cropping histories for the inventory analysis.

Box 5-3: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different nitrogen inputs (i.e., synthetic fertilizer, manure, nitrogen fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total nitrogen applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this *Inventory* is based on application of a process-based model (i.e., DayCent) that represents the interaction of nitrogen inputs, land use and management, as well as environmental conditions at specific locations, such as freeze-thaw effects that generate pulses of N_2O emissions (Wagner-Riddle et al. 2017; Del Grosso et al. 2022). Consequently, the Tier 3 approach accounts for land-use and management impacts and their interaction with environmental factors,

such as weather patterns and soil characteristics, in a more comprehensive manner, which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific nitrogen fertilization rates), additional data inputs (e.g., daily weather, soil types), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate that the method is an improvement over lower tier methods for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding nitrogen cycling. Tier 1 assumes that nitrogen added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that may create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model in the Tier 3 approach includes the legacy effect of nitrogen added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

DayCent is used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat, but is not applied to estimate N_2O emissions from other crops or rotations with other crops,[18] such as sugarcane, some vegetables, and perennial/horticultural crops. Areas that are converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland and settlements, are not simulated with DayCent. DayCent is also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils in the topsoil (greater than 35 percent by volume in the top 30 cm of the soil profile), or to estimate emissions from drained organic soils (*Histosols*). The Tier 3 method has not been fully tested for estimating N_2O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DayCent due to limited activity data on land use histories. For areas that are not included in the DayCent simulations, Tier 1 methods are used to estimate emissions, including (1) direct emissions from nitrogen inputs for crops on mineral soils that are not simulated by DayCent; (2) direct emissions from PRP nitrogen additions on federal grasslands; (3) direct emissions for land application of biosolids (i.e., treated sewage sludge) to soils; and (4) direct emissions from drained organic soils in croplands and grasslands.

A splicing method is used to estimate soil N_2O emissions for 2021 to 2022 at the national scale because new activity data have not been incorporated into the analysis for those years. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions that are derived using the Tier 3 method. Surrogate data for these regression models includes corn and soybean yields from USDA-NASS statistics,[19] and weather data from the PRISM Climate Group (PRISM 2022). For the Tier 1 method, a linear-time series model is used to estimate emissions for 2021-2022 without surrogate data. In addition, the linear time series model is used to estimate emissions data for 2018 to 2022 for other organic nitrogen amendments (i.e., commercial organic fertilizer) due to a gap in the activity data during the latter part of the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). See Box 5-4 for more information about the splicing method. Emission estimates for years with imputed data will be recalculated in future *Inventory* reports when new NRI data and other organic amendment nitrogen data are available.

[18] A small proportion of the major commodity crop production, such as corn and wheat, is included in the Tier 1 analysis because these crops are rotated with other crops or land uses (e.g., forest lands) that are not simulated by DayCent.

[19] See https://quickstats.nass.usda.gov/.

Box 5-4: Data Splicing Method

An approach to extend the time series is needed for agricultural soil management because there are typically activity data gaps at the end of the time series. This is mainly because the NRI survey program, which provides critical information for estimating greenhouse gas emissions and removals, does not release data every year.

Splicing methods have been used to impute missing data at the end of the emission time series for both the Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate emissions based on the emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by the equation:

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil nitrous oxide), Xβ for the Tier 3 method contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. The term Xβ for the Tier 1 method only contains year as a predictor of emission patterns over the time series (change in emissions per year), and therefore, is a linear time series model with no surrogate data. Parameters are estimated using standard statistical techniques, and used in the model described above to predict the missing emissions data.

A critical issue with splicing methods is to account for the additional uncertainty introduced by predicting emissions without compiling the full inventory. Specifically, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This additional uncertainty is quantified within the model framework using a Monte Carlo approach. Consequently, the uncertainty from the original inventory data is combined with the uncertainty in the data splicing model. The approach requires estimating parameters in the data splicing models in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the draws of parameters values that are selected in each Monte Carlo iteration, and used to produce estimates with inventory data). Therefore, the data splicing method generates emissions estimates from each surrogate data model in the Monte Carlo analysis, which are used to derive confidence intervals in the estimates for the missing emissions data. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach for Mineral Cropland Soils

The DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001 and 2011) is used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops (see list in previous section) based on the crop histories in the 2017 NRI (USDA-NRCS 2020) and extended through 2020 using CDL (USDA-NASS 2021). Crops simulated by DayCent are grown on approximately 85 percent of total cropland area in the United States. The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1[20] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2022), and soil attributes from the Soil Survey Geographic

[20] Net Primary Production is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2020. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature, and moisture stress on crop production (see Metherell et al. 1993) but does not incorporate the additional information about crop condition provided with remote sensing data.

Database (SSURGO) (Soil Survey Staff 2020). DayCent is used to estimate direct N_2O emissions due to mineral nitrogen available from the following sources: (1) application of synthetic fertilizers; (2) application of livestock manure; (3) retention of crop residues in the field for nitrogen-fixing legumes and non-legume crops and subsequent mineralization of nitrogen during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); (4) mineralization of nitrogen from decomposition of soil organic matter; and (5) asymbiotic fixation.

Management activity data from several sources supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006 and 2013 to 2016. These data are combined with other datasets in an imputation analysis. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use Gradient Boosting (Friedman 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988, van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. It makes the best predictions at specific NRI survey locations or at state or region level models. The predictive mean matching method identifies the most similar management activity recorded in the CEAP surveys that match the prediction from the gradient boosting algorithm. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the gradient boosting. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2020). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). To determine the trends in tillage management, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and OpTIS Data Product[21] for 2008 to 2020 (Hagen et al. 2020). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). For cover crops, CEAP data are combined with information from USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS[22] data (Hagen et al. 2020). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

The IPCC method considers crop residue nitrogen inputs and nitrogen mineralized from soil organic matter as activity data. However, they are not treated as activity data in DayCent simulations because residue production, symbiotic nitrogen fixation (e.g., legumes), mineralization of nitrogen from soil organic matter, and asymbiotic nitrogen fixation are internally generated by the model as part of the simulation. In other words, DayCent accounts for the influence of symbiotic nitrogen fixation, mineralization of nitrogen from soil organic matter and crop residue retained in the field, and asymbiotic nitrogen fixation on N_2O emissions, but these are not model inputs.

The N_2O emissions from crop residues are reduced by approximately 3 percent (the assumed average burned portion for crop residues in the United States) to avoid double counting associated with non-CO_2 greenhouse gas

[21] OpTIS data on tillage practices provided by Regrow Agriculture, Inc.

[22] OpTIS data on cover crop management provided by Regrow Agriculture, Inc.

emissions from agricultural residue burning. Estimated levels of residue burning are based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996).

Uncertainty in the emission estimates from DayCent is associated with input uncertainty due to missing management data in the NRI survey that is imputed from other sources; model uncertainty due to incomplete specification of carbon and nitrogen dynamics in the DayCent model parameters and algorithms; and sampling uncertainty associated with the statistical design of the NRI survey. Uncertainty is estimated with two variance components (Ogle et al. 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007; Del Grosso et al. 2010). The data is combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2020. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), and random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base. The second variance component is computed using the replicate weights provided with the NRI survey data, and a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are summed to quantify the total uncertainty and produce confidence intervals associated with the estimated emissions.

In order to ensure time-series consistency, the DayCent model is applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for 2021 to 2022 based on the pattern in emissions data from 1990 to 2020 (see Box 5-4). The pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). The time series will be updated with the Tier 3 method in the future as new activity data are incorporated into the analysis.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., nitrogen fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with nitrogen dynamics in the soil profile, including immobilization of nitrogen by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of synthetic nitrogen fertilizer added to the soil, or mineral nitrogen made available through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of nitrogen from the atmosphere, is determined for each nitrogen source and then divided by the total amount of mineral nitrogen in the soil according to the DayCent model simulation. For 2021 to 2022, the contribution of each nitrogen source is based on the average of values that are estimated for 2018 to 2020. The percentages are then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to nitrogen management practices. This approach is only an approximation because it assumes that all nitrogen made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al. 2009). However, this approach allows for further disaggregation of emissions by source of nitrogen, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of nitrogen.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DayCent (e.g., DayCent has not been parametrized to simulate all crop types and some soil types such

as *Histosols*). For the Tier 1 method, estimates of direct N_2O emissions from nitrogen applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) decomposition and mineralization of nitrogen from above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments are only included in the Tier 1 analysis because these data are not available at the county-level, which is necessary for the DayCent simulations. Consequently, all commercial organic fertilizer, as well as manure that is not added to crops in the DayCent simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic nitrogen fertilizer additions for crop areas that are not simulated by DayCent. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS using sales records from 1990 to 2012 (Brakebill and Gronberg 2017). For 2013 through 2017, fertilizer sales data from AAPFCO (AAPFCO 2013 through 2022) [23] after adjusting for the proportion of on-farm application to determine the amount applied to crops. The amount of fertilizer applied after 2017 is estimated using the data splicing method described in Box 5-4 for the linear time series model. Then the portion of fertilizer applied to crops and grasslands simulated by DayCent is subtracted from the on-farm sales data (see Tier 3 Approach for mineral cropland soils and direct N_2O emissions from grassland soils sections for information on data sources), and the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DayCent. At a minimum, 3 percent of state-level on-farm fertilizer sales are assumed to be applied to cropland in the Tier 1 method.
- Similarly, a process-of-elimination approach is used to estimate manure nitrogen additions for crops that are not simulated by DayCent. The total amount of manure available for land application to soils has been estimated with methods described in the manure management section (Section 5.2) and annex (Annex 3.11). The amount of manure nitrogen applied in the Tier 3 approach to crops and grasslands is subtracted from total annual manure nitrogen available for land application (see Tier 3 Approach for mineral cropland soils and direct N_2O emissions from grassland soils sections for information on data sources). This difference is assumed to be applied to crops that are not simulated by DayCent.
- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics through 2017,[24] which are converted from mass of fertilizer to units of nitrogen using average organic fertilizer nitrogen content, ranging between 2.3 to 4.2 percent across the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). Commercial fertilizers include dried manure and biosolids (i.e., treated sewage sludge), but the amounts are removed from the commercial fertilizer data to avoid double counting[25] with the manure nitrogen dataset described above and the biosolids (i.e., treated sewage sludge) amendment data discussed later in this section.
- Crop residue nitrogen is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2020), as extended using the CDL data (USDA-NASS 2021), crop production yield statistics (USDA-NASS 2023), dry matter fractions (IPCC 2006), linear equations to

[23] The fertilizer consumption data in AAPFCO are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b).

[24] Soil N_2O emissions are imputed using data splicing methods for commercial fertilizers, i.e., other organic fertilizers, after 2017 because the activity data are not available.

[25] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and biosolids (i.e., treated sewage sludge) are also included in other datasets in this Inventory. Consequently, the proportions of dried manure and biosolids, which are provided in the reports (TVA 1991 through 1994; AAPFCO 1995 through 2022), are used to estimate the nitrogen amounts in dried manure and biosolids. To avoid double counting, the resulting nitrogen amounts for dried manure and biosolids are subtracted from the total nitrogen in commercial organic fertilizers before estimating emissions using the Tier 1 method.

estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and nitrogen contents of the residues (IPCC 2006). Nitrogen inputs from residue were reduced by 3 percent to account for average residue burning portions in the United States.

The total amounts of soil mineral nitrogen from applied synthetic and organic fertilizers, manure nitrogen additions and crop residues are multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 method. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 1 methods are applied from 1990 to 2020, and a linear extrapolation method[26] is used to approximate emissions for 2021 to 2022 based on the emission patterns between 1990 and 2020 (see Box 5-4). The exceptions include crop residue nitrogen which is estimating using the Tier 1 method for 1990 to 2022 with no linear extrapolation, and for other organic nitrogen fertilizers (i.e., commercial fertilizers), which are estimated with linear time series model for 2018 to 2022 due to a gap in the activity data during the latter part of the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). For the extrapolation, the emission pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). As with the Tier 3 method, the time series that is based on the splicing methods will be recalculated in a future *Inventory* report with updated activity data.

Tier 1 and 3 Approaches from Mineral Grassland Soils

As with N_2O emissions from croplands, the Tier 3 process-based approach with application of the DayCent model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure nitrogen additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass or mixed grass/legume forage primarily for livestock grazing. Rangelands are extensive areas of native grassland that are not intensively managed, while pastures are seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation, fertilization, or inter-seeding legumes. DayCent is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2020) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), nitrogen fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as daily spread or manure collected from other animal waste management systems such as lagoons and digesters), and synthetic fertilizer application. Other nitrogen inputs are simulated within the DayCent framework, including nitrogen input from mineralization due to decomposition of soil organic matter and nitrogen inputs from senesced grass litter, as well as asymbiotic fixation of nitrogen from the atmosphere. The simulations used the same weather, soil, and synthetic nitrogen fertilizer data as discussed under the Tier 3 Approach in the mineral cropland soils section. Synthetic nitrogen fertilization rates are based on data from the Carbon Sequestration Rural Appraisals (CSRA) conducted by the USDA-NRCS (USDA-NRCS, unpublished data). The CSRA was a solicitation of expert knowledge from USDA-NRCS staff throughout the United States to support the *Inventory*. Biological nitrogen fixation is simulated within DayCent, and therefore is not an input to the model.

Manure nitrogen deposition from grazing animals in PRP systems (i.e., PRP manure nitrogen) is a key input of nitrogen to grasslands. The amounts of PRP manure nitrogen applied on non-federal grasslands for each NRI survey location are based on the amount of nitrogen excreted by livestock in PRP systems that is estimated in the manure management section (see Section 5.2 and Annex 3.11). The total amount of nitrogen excreted in each county is divided by the grassland area to estimate the nitrogen input rate associated with PRP manure. The resulting rates are a direct input into the DayCent simulations. The nitrogen input is subdivided between urine and dung based on a 50:50 split. DayCent simulations of non-federal grasslands accounted for approximately 71

percent of total PRP manure nitrogen in aggregate across the country.[27] The remainder of the PRP manure nitrogen in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method.

Biosolids (i.e., treated sewage sludge) are assumed to be applied on grasslands.[28] Application of biosolids is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007) (see Section 7.2 for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Biosolids data are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at NRI survey locations. Therefore, DayCent could not be used to simulate the influence of biosolids on N_2O emissions from grassland soils, and consequently, emissions from biosolids are estimated using the IPCC (2006) Tier 1 method.

Soil N_2O emission estimates from DayCent are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). There is also sampling uncertainty for the NRI survey that is quantified with replicate sampling weights associated with the survey, as discussed for Tier 3 method associated with mineral cropland soils. N_2O emissions for the PRP manure nitrogen deposited on federal grasslands and applied biosolids nitrogen are estimated using the Tier 1 method by multiplying the nitrogen input by the default emission factor. Emissions from manure nitrogen are estimated at the state level and aggregated to the entire country, but emissions from biosolids nitrogen are calculated exclusively at the national scale. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2020 based on the Tier 1 and 3 methods, except for biosolids (discussed below). In order to ensure time-series consistency, emissions from 2021 to 2022 are estimated using a splicing method as described in Box 5-4, with a linear extrapolation based on the emission patterns in the 1990 to 2020 data. Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). As with croplands, estimates for 2021 to 2022 will be recalculated in a future *Inventory* when the activity data are updated. Biosolids application data are compiled through 2022 in this *Inventory*, and therefore soil N_2O emissions and confidence intervals are estimated using the Tier 1 method for all years without application of the splicing method.

Tier 1 Approach for Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 method is used to estimate direct N_2O emissions due to drainage of organic soils in croplands and grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2017 NRI (USDA-NRCS 2020), and extended through 2022 using CDL (USDA-NASS 2021) and the Forest Inventory and Analysis (FIA) survey data, which is harmonized with the NRI data (Nelson et al. 2020). Organic soils are identified using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The IPCC climate region map is used to subdivide areas into temperate and tropical climates according to the climate classification from IPCC (2006). To estimate annual emissions, the total temperate area is multiplied by the IPCC default emission factor for temperate regions, and the total tropical area is multiplied by the IPCC default emission factor for tropical regions (IPCC 2006). In order to ensure time-series consistency, the Tier 1 methods are applied from 1990 to 2022.

[27] A small amount of PRP nitrogen (less than 1 percent) is deposited in grazed pasture that is in rotation with annual crops and is reported in the grassland N_2O emissions.

[28] A portion of biosolids may be applied to croplands, but there is no national dataset to disaggregate the amounts between cropland and grassland.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-15 and Table 5-16). Further elaboration on the methodology and data used to estimate soil N_2O emissions are described in Annex 3.12.

Indirect N_2O Emissions Associated with Nitrogen Management in Cropland and Grasslands

Indirect N_2O emissions occur when synthetic nitrogen applied or made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of nitrogen as NO_x (nitrogen oxides) and NH_3 (ammonia) following application of synthetic fertilizer, organic amendments (e.g., manure, biosolids), and deposition of PRP manure. Nitrogen made available from mineralization of soil organic matter and residue, including nitrogen incorporated into crops and forage from symbiotic nitrogen fixation, and input of nitrogen from asymbiotic fixation also contributes to volatilized nitrogen emissions. Volatilized nitrogen can be returned to soils through atmospheric deposition, and a portion of the deposited nitrogen is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil nitrogen (primarily in the form of NO_3^-, i.e., nitrate) that is made available through anthropogenic activity on managed lands, including organic and synthetic fertilization, organic amendments, mineralization of soil organic matter and residue, and inputs of nitrogen into the soil from asymbiotic fixation. Nitrate is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the nitrogen for reporting purposes, which here includes croplands and grasslands.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Atmospheric Deposition of Volatilized Nitrogen

The Tier 3 DayCent model and IPCC (2006) Tier 1 methods are combined to estimate the amount of nitrogen that is volatilized and eventually emitted as N_2O. DayCent is used to estimate nitrogen volatilization for land areas whose direct emissions are simulated with DayCent (i.e., most commodity and some specialty crops and most grasslands). The nitrogen inputs included are the same as described for direct N_2O emissions in the Tier 3 approach for mineral cropland and grassland soils sections. Nitrogen volatilization from all other areas is estimated using the Tier 1 method with default IPCC fractions for nitrogen subject to volatilization (i.e., synthetic and manure nitrogen on croplands not simulated by DayCent, other organic nitrogen inputs (i.e., commercial fertilizers), PRP manure nitrogen excreted on federal grasslands, and biosolids [i.e., treated sewage sludge] application on grasslands).

The IPCC (2006) default emission factor is multiplied by the amount of volatilized nitrogen generated from both DayCent and Tier 1 methods to estimate indirect N_2O emissions occurring with re-deposition of the volatilized nitrogen from 1990-2020 (see Table 5-18). A linear extrapolation data splicing method, described in Box 5-4, is applied to estimate emissions from 2021 to 2022 based on the emission patterns from 1990 to 2020. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized nitrogen, the Tier 3 DayCent model and IPCC (2006) Tier 1 method are combined to estimate the amount of nitrogen that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DayCent is used to simulate the amount of nitrogen transported from lands in the Tier 3 Approach. Nitrogen transport from all other areas is estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of nitrogen subject to leaching and runoff associated with

nitrogen applications on croplands that are not simulated by DayCent, applications of biosolids on grasslands, other organic N fertilizer applications, crop residue nitrogen inputs, and PRP manure nitrogen excreted on federal grasslands.

For both the DayCent Tier 3 and IPCC (2006) Tier 1 methods, NO_3^- leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions, as discussed in IPCC (2006). In the United States, the threshold for significant NO_3^- leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation does not exceed 80 percent of PET (Note: All irrigated systems are assumed to have significant amounts of leaching of nitrogen even in drier climates).

For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (see Table 5-18). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

In order to ensure time-series consistency, indirect soil N_2O emissions are estimated using the Tier 1 and 3 approaches from 1990 to 2020 and then a linear extrapolation data splicing method, described in Box 5-4, is applied to estimate emissions from 2021 to 2022 based on the emission patterns from 1990 to 2020. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the direct N_2O emissions, the time series will be recalculated in a future *Inventory* when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DayCent; (2) the components of indirect emissions (nitrogen volatilized and leached or runoff) simulated by DayCent; (3) direct emissions estimated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (nitrogen volatilized and leached or runoff) estimated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions as well as the components of indirect emissions that are estimated from DayCent are derived from two variance components (Ogle et al. 2010). For the first component, a Monte Carlo Analysis (consistent with IPCC Approach 2) is used to address uncertainties in management activity data as well as model parameterization and structure (Del Grosso et al. 2010). The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire land base, and computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For 2021 to 2022 (and 2018 to 2022 for other organic nitrogen fertilizers) there is additional uncertainty propagated through the Monte Carlo Analysis associated with the splicing method (See Box 5-4) except for the Tier 1 method for biosolids and crop residue nitrogen inputs, which do not use the data splicing method for 2021 to 2022.

Simple error propagation methods (IPCC 2006) are used to derive confidence intervals for direct emissions estimated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions. Uncertainty in the splicing method is also included in the error propagation for 2021-2022 (see Box 5-4). Additional details on the uncertainty methods are provided in Annex 3.12. Table 5-19 shows the combined uncertainty for soil N_2O emissions. The estimated direct soil N_2O emissions range from 28 percent below to 28 percent above the 2022 emission estimate of 262.5 MMT CO_2 Eq. The combined uncertainty for indirect soil N_2O emissions ranges from 51 percent below to 123 percent above the 2022 estimate of 28.3 MMT CO_2 Eq.

Table 5-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2022 (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	262.5	189.6	335.3	-28%	+28%
Indirect Soil N_2O Emissions	N_2O	28.3	13.7	63.3	-51%	+123%

Note: Due to lack of data, uncertainties in PRP manure nitrogen production, other organic fertilizer amendments, and biosolids (i.e., treated sewage sludge) amendments to soils are currently treated as certain. These sources of uncertainty will be included in a future *Inventory* (IPCC 2006).

Additional uncertainty is associated with an incomplete estimation of N_2O emissions from managed croplands and grasslands in Hawaii and Alaska. The *Inventory* currently includes the N_2O emissions from managed manure and PRP nitrogen, and biosolid additions for Alaska and managed manure and PRP nitrogen, biosolid additions, and crop residue for Hawaii. Land areas used for agriculture in Alaska and Hawaii are small relative to major crop commodity states in the conterminous United States, so the emissions are likely to be minor for the other sources of nitrogen (e.g., synthetic fertilizer and crop residue inputs). Regardless, there is a planned improvement to include the additional sources of emissions in a future *Inventory*.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. DayCent results for N_2O emissions and NO_3^- leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005; Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data for cropland are available for 64 sites with 769 observations of management practice effects, and measurement data for grassland are available for 12 sites with 88 observations of management practice effects. Nitrate leaching data are available for 14 sites, representing 432 observations of management practice effects. In general, DayCent predicted N_2O emission and nitrate leaching for these sites reasonably well. See Annex 3.12 for more detailed information about the comparisons.

Databases containing input data and probability distribution functions required for DayCent simulations of croplands and grasslands and unit conversion factors have been checked. In addition, program scripts that are used to run the Monte Carlo uncertainty analysis have been checked. Errors were found in the synthetic nitrogen application rates for the Tier 3 method for a subset of years in some states, with overapplication based on comparisons to the synthetic fertilizer sales data. An error in the uncertainty calculation was found due to improper formulation of land area variances. A minor error was also identified in manure deposited in pasture, range, and paddock. Databases containing input data, emission factors, and calculations required for the Tier 1 method have been checked and updated as needed. Quality control identified a problem with error propagation in the Tier 1 uncertainty analysis associated with the emission factors. There was also an error identified in the leaching calculation based on irrigation status. All of these errors were corrected. Links between spreadsheets have also been checked, updated, and corrected as needed.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations, including a) updated time series of land representation data (Nelson et al. 2020), b) re-calibration of the soil carbon module in the DayCent model (See Annex 3.12); c) a more accurate output variable to estimate asymbiotic nitrogen fixation in

the Tier 3 method, and d) corrections associated with manure deposited on pasture, range and paddock in addition to estimation of leaching based on irrigation status. The combined impact from these changes resulted in an average annual increase in emissions of 3.3 MMT CO_2 Eq., or 1.1 percent, from 1990 to 2021 relative to the previous *Inventory*.

Planned Improvements

Several planned improvements are underway associated with improving the DayCent biogeochemical model. These improvements include a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature and water stress effects on plant production will be further improved in DayCent with additional model calibration. In addition, there is an improvement underway to calibrate the nitrogen submodule in order to more accurately predict nitrogen-gas losses and nitrate leaching rates. Experimental study sites will continue to be added for quantifying model structural uncertainty with priority given to studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013). In addition, improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (see Section 5.7).

For Tier 1, there is a planned improvement to include all sources of nitrogen for Alaska and Hawaii in the *Inventory* for agricultural soil management, which currently only addresses managed manure nitrogen and PRP nitrogen, and biosolids additions for grasslands in both states, in addition to crop residue nitrogen inputs for Hawaii. There is also an improvement to incorporate the Tier 1 emission factor for N_2O emissions from drained organic soils by using the revised factors in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). There is a planned improvement for the Tier 1 method associated with estimating soil N_2O emissions from nitrogen mineralization due to soil organic matter decomposition that is accelerated with land use conversions to cropland and grassland. Lastly, a review of available data on biosolids (i.e., treated sewage sludge) application will also be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Improvements are expected to be completed for the next *Inventory* (i.e., 2025 submission to the UNFCCC, 1990 through 2023 *Inventory*), pending prioritization of resources.

5.5 Liming (CRT Source Category 3G)

Crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are added to soils by land managers to increase soil pH (i.e., to reduce acidification). Carbon dioxide emissions occur as these compounds react with hydrogen ions in soils. The rate of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production, etc.) are reported in the IPPU chapter. Emissions from liming of soils have fluctuated between 1990 and 2022 in the United States, ranging from 2.2 MMT CO_2 Eq. to 6.0 MMT CO_2 Eq. across the entire time series. In 2022, liming of soils in the United States resulted in emissions of 3.3 MMT CO_2 Eq. (0.9 MMT C), representing a 30 percent decrease in emissions since 1990 (see Table 5-20 and Table 5-21). The trend is driven by variation in the amount of limestone and dolomite applied to soils over the time period.

Table 5-20: Emissions from Liming (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Limestone	4.1	3.9	2.0	1.9	2.5	2.0	2.9
Dolomite	0.6	0.4	0.2	0.3	0.4	0.4	0.3
Total	**4.7**	**4.4**	**2.2**	**2.2**	**2.9**	**2.4**	**3.3**

Note: Totals may not sum due to independent rounding.

Table 5-21: Emissions from Liming (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Limestone	1.1	1.1	0.6	0.5	0.7	0.5	0.8
Dolomite	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Total	**1.3**	**1.2**	**0.6**	**0.6**	**0.8**	**0.7**	**0.9**

+ Does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite, which are applied to soils (see Table 5-22), were multiplied by CO_2 emission factors from West and McBride (2005). These country-specific emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of carbonates that are transported from soils through hydrological processes and eventually deposited in ocean basins (West and McBride 2005). This analysis of lime dissolution is based on studies in the Mississippi River basin, where the vast majority of lime application occurs in the United States (West 2008). Moreover, much of the remaining lime application is occurring under similar precipitation regimes, and so the emission factors are considered a reasonable approximation for all lime application in the United States (West 2008) (see Box 5-5).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey (USGS) *Minerals Yearbook* (Tepordei 1994 through 2015; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014, 2015, 2016, 2017, 2020a, 2022a, 2022b, 2022c, 2023a), as well as preliminary data that will eventually be published in the *Minerals Yearbook* for the latter part of the time series (Willett 2023b). Data for the final year of the inventory is based on the *Mineral Industry Surveys*, as discussed below (USGS 2023). The U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) compiled production and use information through surveys of crushed stone manufacturers. However, manufacturers provided different levels of detail in survey responses so the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production).

Box 5-5: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of soils were estimated using a Tier 2 methodology based on emission factors specific to the United States that are lower than the IPCC (2006) default emission factors. Most lime application in the United States occurs in the Mississippi River basin, or in areas that have similar soil and rainfall regimes as the Mississippi River basin. Under these conditions, a significant portion of dissolved agricultural lime leaches through the soil into groundwater. Groundwater moves into channels and is transported to larger rivers and eventually the ocean where $CaCO_3$ precipitates to the ocean floor (West and McBride 2005). The U.S.-specific emission factors (0.059 metric ton C/metric ton limestone and 0.064 metric ton C/metric ton dolomite) are about half of the IPCC (2006) emission factors (0.12 metric ton C/metric ton limestone and 0.13 metric ton

C/metric ton dolomite). For comparison, the 2022 U.S. emission estimate from liming of soils is 3.3 MMT CO_2 Eq. using the country-specific factors. In contrast, emissions would be estimated at 6.6 MMT CO_2 Eq. using the IPCC (2006) default emission factors.

Data on "specified" limestone and dolomite amounts were used directly in the emission calculation because the end use is provided by the manufacturers and can be used to directly determine the amount applied to soils. However, it is not possible to determine directly how much of the limestone and dolomite is applied to soils for manufacturer surveys in the "unspecified" and "estimated" categories. For these categories, the amounts of crushed limestone and dolomite applied to soils were determined by multiplying the percentage of total "specified" limestone and dolomite production that is applied to soils, by the total amounts of "unspecified" and "estimated" limestone and dolomite production. In other words, the proportion of total "unspecified" and "estimated" crushed limestone and dolomite that was applied to soils is proportional to the amount of total "specified" crushed limestone and dolomite that was applied to soils.

In addition, data were not available for 1990, 1992, and 2022 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2022 data, 2021 fractions were applied to the 2022 estimates of total crushed stone. The basis for these estimates is from the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2023* (USGS 2023).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1996 and by the USGS from 1997 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Table 5-22: Applied Minerals (MMT)

Mineral	1990	2005	2018	2019	2020	2021	2022
Limestone	19.0	18.1	9.4	8.9	11.6	9.3	13.5
Dolomite	2.4	1.9	0.9	1.2	1.6	1.6	1.5

The same methods are applied throughout the time series. The activity data are extended in the last two years of the time series based on proportions of specified, unspecified and estimated agricultural limestone and dolomite so that estimates are consistent with the previous year's data. These years will be recalculated when additional data are available on the amounts of limestone and dolomite that are used for agricultural purposes.

Uncertainty

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not addressed in this analysis, but is assumed to be a relatively small contributor to the overall uncertainty (West 2005). The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty. The emission factor distributions were truncated at 0 so that emissions were not less than 0.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO_2 emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-23. Carbon dioxide emissions from carbonate lime application to soils in 2022 were estimated to be between 0.50 and 6.18 MMT CO_2 Eq. at the 95 percent confidence level. This confidence interval represents a range of 85 percent below to 89 percent above the 2022 emission estimate of 3.3 MMT CO_2 Eq. Some carbon in the carbonate lime applied to agricultural soils is not emitted to the atmosphere due to the dominance of the carbonate lime dissolving in carbonic acid rather than nitric acid (West and McBride 2005).

Table 5-23: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming	CO_2	3.3	0.50	6.18	-85%	+89%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The quality control effort focused on the Tier 1 procedures for this *Inventory*, and no errors were identified in this *Inventory*.

Recalculations Discussion

Limestone and dolomite application data for 2020 and 2021 were updated with the recent published data from Willett, J.C. (2023a). With these revisions, the emissions decreased by 1 and 22 percent for 2020 and 2021 (respectively) relative to the previous *Inventory*.

Planned Improvements

At this time there are no specific planned improvements for estimating emissions from liming.

5.6 Urea Fertilization (CRT Source Category 3H)

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to greenhouse gas emissions through the release of CO_2 that was fixed during the production of urea. In the presence of water and urease enzymes, urea that is applied to soils as fertilizer is converted into ammonium (NH_4^+), hydroxyl ion (OH), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States were 5.3 MMT CO_2 Eq. (1.5 MMT C) in 2022 (Table 5-24 and Table 5-25). Carbon dioxide emissions have increased by 120 percent between 1990 and 2022 due to an increasing amount of urea that is applied to soils. The variation in emissions across the time series is driven by differences in the amounts of fertilizer applied to soils each year. Carbon dioxide emissions associated with urea used for non-agricultural purposes are reported in the IPPU chapter (Section 4.6).

Table 5-24: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Fertilization	2.4	3.5	4.9	5.0	5.1	5.2	5.3

Table 5-25: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Fertilization	0.7	1.0	1.3	1.4	1.4	1.4	1.5

Methodology and Time-Series Consistency

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology following the *2006 IPCC Guidelines* Figure 11.5 decision tree for CO_2 emissions from urea fertilization.[29] The method assumes that carbon in the urea is released after application to soils and converted to CO_2. The annual amounts of urea applied to croplands (see Table 5-26) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizer* reports (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2022).[30] These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of carbon per metric ton of urea), which is equal to the carbon content of urea on an atomic weight basis. National estimates from urea fertilization also include emissions from Puerto Rico.

Fertilizer sales data are reported in fertilizer years (July previous year through June current year), so a calculation was performed to convert the data to calendar years (January through December). According to monthly fertilizer use data (TVA 1992b), 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year, and 65 percent is applied between January and June of the current calendar year.

Fertilizer sales data for the 2018 through 2022 fertilizer years were not available for this *Inventory*. Therefore, urea application in the 2018 through 2022 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2013 through 2017) at the state scale. A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-annual variability in consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States. The fertilizer year data is then converted into calendar year (Table 5-26) data using the method described above.

Table 5-26: Applied Urea (MMT)

	1990	2005	2018	2019	2020	2021	2022
Urea Fertilizer[a]	3.3	4.8	6.7	6.9	7.0	7.1	7.3

[a] These numbers represent amounts applied to all agricultural land, including cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, settlements remaining settlements, land converted to settlements, forest land remaining forest land and land converted to forest land, as it is not currently possible to apportion the data by land-use/conversion category.

The same methods were applied to the entire time series to ensure time-series consistency from 1990 through 2022. In addition, activity data are extended using a data splicing method with a linear extrapolation based on the last five years of urea fertilization data to ensure consistency in the time series. These years will be recalculated when additional data are available on urea fertilization.

[29] *2006 IPCC Guidelines* Volume 4, Chapter 11, Figure 11.5 (page 11.33)

[30] The amount of urea consumed for non-agricultural purposes in the United States is reported in the Industrial Processes and Product Use chapter, Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Uncertainty

An Approach 2 Monte Carlo analysis is conducted as described by the IPCC (2006). The largest source of uncertainty is the default emission factor, which assumes that 100 percent of the carbon in $CO(NH_2)_2$ applied to soils is emitted as CO_2. The uncertainty surrounding this factor incorporates the possibility that some of the carbon may not be emitted to the atmosphere, and therefore the uncertainty range is set from 50 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, urea consumption data have uncertainty that is represented as a normal density. Due to the highly skewed distribution of the resulting emissions from the Monte Carlo uncertainty analysis, the estimated emissions are based on the analytical solution to the equation, and the confidence interval is approximated based on the values at 2.5 and 97.5 percentiles.

Carbon dioxide emissions from urea fertilization of agricultural soils in 2022 are estimated to be between 3.05 and 5.49 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2022 emission estimate of 5.33 MMT CO_2 Eq. (Table 5-27).

Table 5-27: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	5.33	3.05	5.49	-43%	+3%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

There are additional uncertainties that are not quantified in this analysis. There is uncertainty surrounding the assumptions underlying conversion of fertilizer years to calendar years. These uncertainties are negligible over multiple years because an over- or under-estimated value in one calendar year is addressed with a corresponding increase or decrease in the value for the subsequent year. In addition, there is uncertainty regarding the fate of carbon in urea that is incorporated into solutions of urea ammonium nitrate (UAN) fertilizer. Emissions of CO_2 from UAN applications to soils are not estimated in the current *Inventory* (see Planned Improvements).

QA/QC and Verification

A source-specific QA/QC plan for Urea Fertilization has been developed and implemented, consistent with the U.S. Inventory QA/QC plan. No quality control problems were discovered in this process except a correction to the emissions factor value in documentation tables.

Recalculations Discussion

Fertilizer consumption data was updated with the latest published estimate. In turn, the fertilizer values were recalculated using the data splicing method for 2018 to 2021 based on the revised fertilizer amount for 2017. This update led to an average decrease in emissions for the years 2017 through 2021 of 0.01 MMT CO_2 Eq., or 0.1 percent. The remainder of the time series was not affected.

Planned Improvements

A key planned improvement is to incorporate Urea Ammonium Nitrate (UAN) in the estimation of Urea CO_2 emissions. Activity data for UAN have been identified, but additional information is needed to fully incorporate this type of fertilizer into the analysis, which will be completed in a future *Inventory*.

5.7 Field Burning of Agricultural Residues (CRT Source Category 3F)

Crop production creates large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be left in the field and possibly incorporated into the soil with tillage; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; transported to landfills; or burned in the field. The *2006 IPCC Guidelines* does not consider field burning of crop residues to be a net source of CO_2 emissions because it is assumed the carbon released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season by the crop (IPCC 2006). However, crop residue burning is a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

In the United States, field burning of agricultural residues occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane and wheat (McCarty 2009). In 2022, CH_4 and N_2O emissions from field burning of agricultural residues were 0.6 MMT CO_2 Eq. (22 kt) and 0.2 MMT CO_2 Eq. (1 kt), respectively (Table 5-28 and Table 5-29). Annual emissions of CH_4 and N_2O have increased from 1990 to 2022 by 14 percent and 16 percent, respectively. The increase in emissions over time is partly due to higher yielding crop varieties with larger amounts of residue production and fuel loads, but also linked with an increase in the area burned for some crop types.

Table 5-28: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2018	2019	2020	2021	2022
CH_4	**0.5**	**0.6**	**0.6**	**0.7**	**0.6**	**0.6**	**0.6**
Sugarcane	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Wheat	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Maize	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	0.0	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Lentils	0.0	+	+	+	+	+	+
Chickpeas	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Wheat	0.1	0.1	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+

Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	0.0	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	0.0	+	+	+	+	+	+
Chickpeas	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**0.7**	**0.8**	**0.8**	**0.9**	**0.8**	**0.8**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-29: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2018	2019	2020	2021	2022
CH_4	**19**	**23**	**22**	**23**	**22**	**22**	**22**
Sugarcane	4	6	5	6	5	5	5
Wheat	6	6	5	5	5	5	5
Maize	2	4	5	5	5	5	5
Rice	3	3	2	3	2	3	3
Soybeans	1	2	2	2	2	2	2
Cotton	1	2	1	1	1	1	1
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	0	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Lentils	0	+	+	+	+	+	+
Chickpeas	0	0	0	0	0	0	0
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Wheat	+	+	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+

Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	0	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	0	+	+	+	+	+	+
Chickpeas	0	0	0	0	0	0	0
CO	**407**	**480**	**433**	**468**	**446**	**480**	**501**
NOx	**16**	**18**	**17**	**18**	**17**	**18**	**19**

+ Does not exceed 0.5 kt CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

A country-specific Tier 2 method is used to estimate greenhouse gas emissions from field burning of agricultural residues from 1990 to 2014 (for more details comparing the country-specific approach to the IPCC (2006) default approach, see Box 5-6), and a data splicing method with a linear extrapolation is applied to complete the emissions time series from 2015 to 2022. The exception is sugarcane for which emissions have been estimated from 1990 to 2020, with 2021 to 2022 estimated with the data splicing method. The following equation is used to estimate the amounts of carbon and nitrogen released (R_i, where *i* is *C* or *N*) from burning.

Equation 5-1: Elemental C or N Released through Oxidation of Crop Residues

$$R_i = CP \times RCR \times DMF \times F_i \times FB \times CE$$

$$FB = \frac{AB}{CAH}$$

where,

Crop Production (CP)	=	Annual production of crop, by state, kt crop production
Residue: Crop Ratio (RCR)	=	Amount of residue produced per unit of crop production, kt residue/kt crop production
Dry Matter Fraction (DMF)	=	Amount of dry matter per unit of residue biomass for a crop, kt residue dry matter/ kt residue biomass
Fraction C or N (F_i)	=	Fraction of C or N per unit of dry matter for a crop, kt C or N /kt residue dry matter
Fraction Burned (FB)	=	Proportion of residue biomass consumed, unitless
Combustion Efficiency (CE)	=	Proportion of residue actually burned, unitless
Area Burned (AB)	=	Total area of crop burned, by state, ha
Crop Area Harvested (CAH)	=	Total area of crop harvested, by state, ha

Crop production data are available by state and year from USDA-NASS (2019) for 22 crops that are burned in the conterminous United States, including maize, rice, wheat, barley, oats, other small grains, sorghum, cotton, grass hay, legume hay, peas, sunflower, tobacco, vegetables, chickpeas, dry beans, lentils, peanuts, soybeans, potatoes,

sugarbeets, and sugarcane.[31] Crop area data are based on the 2015 and 2017 National Resources Inventories (NRI) (USDA-NRCS 2018; USDA-NRCS 2020). To estimate total crop production, the crop yield data from USDA Quick Stats (USDA-NASS 2019) are multiplied by the area data for these crops from the NRI survey. The production data for the crop types are presented in Table 5-30. Alaska and Hawaii are not included in the current analysis, but there is a planned improvement to estimate residue burning emissions for these two states in a future *Inventory*.

The amount of elemental carbon or nitrogen released through oxidation of the crop residues is used in the following equation to estimate the amount of CH_4, CO, N_2O, and NO_x emissions (E_g, where g is the specific gas, i.e., CH_4, CO, N_2O, and NO_x) from the field burning of agricultural residues:

Equation 5-2: Emissions from Crop Residue Burning

$$E_g = R_i \times EF_g \times CF$$

where,

Emission ratio (EF_g) = emission ratio by gas, g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released

Conversion Factor (CF) = conversion by molecular weight ratio of CH_4-C to C (16/12), CO-C to C (28/12), N_2O-N to N (44/28), or NO_x-N to N (30/14)

Box 5-6: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather than emission rates related to the amount of carbon and nitrogen in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this *Inventory* includes emissions from twenty-one crops.

A comparison of the methods in the current Inventory and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

Equation 5-3: Estimation of Greenhouse Gas Emissions from Fire

$$Emissions\ (kt) = AB \times M_B \times C_f \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)

[31] Kentucky bluegrass (produced on farms for turf grass installations) may have small areas of burning that are not captured in the sample of locations that were used in the remote sensing analysis (see Planned Improvements).

Mass of Fuel (M_B) = U.S.- Specific Values using NASS Statistics[32] (metric tons dry matter)

Combustion Factor (C_f) = IPCC (2006) default combustion factor with fuel biomass consumption (metric tons dry matter ha^{-1})

Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) Tier 1 method approach resulted in 21 percent lower emissions of CH_4 and 40 percent lower emissions of N_2O compared to this *Inventory*. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific carbon and nitrogen content of the fuel, which is converted into CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Emissions from field burning of agricultural residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather than emission rates related to the amount of carbon and nitrogen in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this *Inventory* includes emissions from 21 crops.

A comparison of the methods in the current *Inventory* and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

Equation 5-4: Estimation of Greenhouse Gas Emissions from Fire

$$Emissions\ (kt) = AB \times M_B \times C_f \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)

Mass of Fuel (M_B) = U.S.- Specific Values using NASS Statistics[33] (metric tons dry matter)

Combustion Factor (C_f) = IPCC (2006) default combustion factor with fuel biomass consumption (metric tons dry matter ha^{-1})

Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) Tier 1 method approach resulted in 21 percent lower emissions of CH_4 and 40 percent lower emissions of N_2O compared to this *Inventory*. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific carbon and nitrogen content of the fuel, which is converted into

[32] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the *Inventory*.

[33] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the *Inventory*.

CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Table 5-30: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2010	2018	2019	2020
Maize	296,065	371,256	398,618	NE	NE	NE
Rice	9,543	11,751	11,976	NE	NE	NE
Wheat	79,805	68,077	68,530	NE	NE	NE
Barley	9,281	5,161	3,942	NE	NE	NE
Oats	5,969	2,646	2,364	NE	NE	NE
Other Small Grains	2,651	2,051	1,803	NE	NE	NE
Sorghum	23,687	14,382	14,052	NE	NE	NE
Cotton	4,605	6,106	4,638	NE	NE	NE
Grass Hay	44,150	49,880	46,761	NE	NE	NE
Legume Hay	90,360	91,819	85,813	NE	NE	NE
Peas	51	660	839	NE	NE	NE
Sunflower	1,015	1,448	1,212	NE	NE	NE
Tobacco	1,154	337	470	NE	NE	NE
Vegetables	+	1,187	1,469	NE	NE	NE
Chickpeas	+	5	+	NE	NE	NE
Dry Beans	467	1,143	1,461	NE	NE	NE
Lentils	+	101	254	NE	NE	NE
Peanuts	1,856	2,176	1,925	NE	NE	NE
Soybeans	56,612	86,980	95,198	NE	NE	NE
Potatoes	18,924	20,026	19,279	NE	NE	NE
Sugarbeets	24,951	25,635	33,336	NE	NE	NE
Sugarcane	26,047	38,928	34,252	36,680	37,361	42,400

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
NE (Not Estimated)
Note: The amount of crop production has not been compiled for 2015 to 2021 so a data splicing method is used to estimate emissions for this portion of the time series.

The area burned is determined based on an analysis of remote sensing products (McCarty et al. 2009, 2010, 2011). The presence of fires has been analyzed at 3,600 survey locations in the NRI from 1990 to 2002 with LANDFIRE data products developed from 30 m Landsat imagery (LANDFIRE 2008), and from 2003 through 2014 using 1 km Moderate Resolution Imaging Spectroradiometer imagery (MODIS) Global Fire Location Product (MCD14ML), combining observations from Terra and Aqua satellites (Giglio et al. 2006). A sample of states are included in the analysis with high, medium and low burning rates for agricultural residues, including Arkansas, California, Florida, Indiana, Iowa and Washington. The area burned is determined directly from the analysis for these states for all crops, with the exception of sugarcane as discussed later in this section.

For other states within the conterminous United States, the area burned for the 1990 through 2014 portion of the time series is estimated from a logistical regression model that has been developed from the data collected from the remote sensing products for the six states. The logistical regression model is used to predict occurrence of fire events. Several variables are tested in the logistical regression including a) the historical level of burning in each state (high, medium or low levels of burning) based on an analysis by McCarty et al. (2011), b) year that state laws limit burning of fields, in addition to c) mean annual precipitation and mean annual temperature from a 4-kilometer gridded product from the PRISM Climate Group (2015). A K-fold model fitting procedure is used due to low frequency of burning and likelihood that outliers could influence the model fit. Specifically, the model is trained with a random selection of sample locations and evaluated with the remaining sample. This process is repeated ten times to select a model that is most common among the set of ten, and avoid models that appear to be influenced by outliers due to the random draw of survey locations for training the model. In order to address

uncertainty, a Monte Carlo analysis is used to sample the parameter estimates for the logistical regression model and produce one thousand estimates of burning for each crop in the remaining forty-two states included in this *Inventory*. State-level area burned data are divided by state-level crop area data to estimate the percent of crop area burned by crop type for each state. Table 5-31 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

Table 5-31: U.S. Average Percent Crop Area Burned by Crop (Percent)

Crop	1990	2005	2010	2018	2019	2020
Maize	+	+	+	NE	NE	NE
Rice	12%	11%	12%	NE	NE	NE
Wheat	3%	3%	2%	NE	NE	NE
Barley	1%	1%	1%	NE	NE	NE
Oats	1%	1%	1%	NE	NE	NE
Other Small Grains	5%	4%	4%	NE	NE	NE
Sorghum	1%	1%	1%	NE	NE	NE
Cotton	7%	10%	9%	NE	NE	NE
Grass Hay	+	+	+	NE	NE	NE
Legume Hay	+	+	+	NE	NE	NE
Peas	1%	1%	1%	NE	NE	NE
Sunflower	+	+	+	NE	NE	NE
Tobacco	1%	1%	1%	NE	NE	NE
Vegetables	+	+	+	NE	NE	NE
Chickpeas	+	+	+	NE	NE	NE
Dry Beans	+	+	+	NE	NE	NE
Lentils	+	1%	1%	NE	NE	NE
Peanuts	5%	5%	5%	NE	NE	NE
Soybeans	1%	1%	1%	NE	NE	NE
Potatoes	+	+	+	NE	NE	NE
Sugarbeets	+	+	+	NE	NE	NE
Sugarcane	6%	5%	6%	4%	6%	4%

+ Does not exceed 0.5 percent.
NE (Not Estimated)

The method for estimating burned area of sugarcane is similar to the approach for other crops. Areas with sugarcane production are identified in the 2017 USDA NRI survey (USDA-NRCS 2020) based on Cropland Data Layer (USDA-NASS 2021).[34] We use the MODIS burned area product from 2002 to 2020 to identify NRI survey locations with sugarcane production that have residue burning, similar to the process for other crops described above (Giglio et al. 2015). However, area of residue burning for sugarcane was estimated for 1990 to 2001 using a linear extrapolation of the area burned from 2002 to 2020, instead of analyzing the remote sensing data for this portion of the time series. This approach is a common data splicing method for filling data gaps in time series (IPCC 2006).

Additional parameters are needed to estimate emissions from the area that has residue burning, including residue: crop ratios, dry matter fractions, carbon fractions, nitrogen fractions and combustion efficiency. Residue: crop product mass ratios, residue dry matter fractions, and the residue N contents are obtained from several sources (IPCC 2006 and sources at bottom of Table 5-32). The residue carbon contents for all crops are based on IPCC (2006) default value for herbaceous biomass. The combustion efficiency is assumed to be 90 percent for all crop types (IPCC/UNEP/OECD/IEA 1997). See Table 5-32 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases are based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-33).

[34] USDA-NRI program aggregates sugarcane with other crops, but areas planted with sugarcane are identified in the USDA-NASS Crop Data Layer.

Table 5-32: Parameters for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction	Combustion Efficiency (Fraction)
Maize	0.707	0.56	0.47	0.01	0.90
Rice	1.340	0.89	0.47	0.01	0.90
Wheat	1.725	0.89	0.47	0.01	0.90
Barley	1.181	0.89	0.47	0.01	0.90
Oats	1.374	0.89	0.47	0.01	0.90
Other Small Grains	1.777	0.88	0.47	0.01	0.90
Sorghum	0.780	0.60	0.47	0.01	0.90
Cotton	7.443	0.93	0.47	0.01	0.90
Grass Hay	0.208	0.90	0.47	0.02	0.90
Legume Hay	0.290	0.67	0.47	0.01	0.90
Peas	1.677	0.91	0.47	0.01	0.90
Sunflower	1.765	0.88	0.47	0.01	0.90
Tobacco	0.300	0.87	0.47	0.01	0.90
Vegetables	0.708	0.08	0.47	0.01	0.90
Chickpeas	1.588	0.91	0.47	0.01	0.90
Dry Beans	0.771	0.90	0.47	0.01	0.90
Lentils	1.837	0.91	0.47	0.02	0.90
Peanuts	1.600	0.94	0.47	0.02	0.90
Soybeans	1.500	0.91	0.47	0.01	0.90
Potatoes	0.379	0.25	0.47	0.02	0.90
Sugarbeets	0.196	0.22	0.47	0.02	0.90
Sugarcane	0.410	0.25	0.47	0.02	0.90

NE (Not Estimated)

Notes: Chickpeas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Cotton: Combined sources (Heitholt et al. 1992; Halevy 1976; Wells and Meredith 1984; Sadras and Wilson 1997; Pettigrew and Meredith 1997; Torbert and Reeves 1994; Gerik et al. 1996; Brouder and Cassmen 1990; Fritschi et al. 2003; Pettigrew et al. 2005; Bouquet and Breitenbeck 2000; Mahroni and Aharonov 1964; Bange and Milroy 2004; Hollifield et al. 2000; Mondino et al. 2004; Wallach et al. 1978).

Lentils: IPCC (2006), Table 11.2; Beans & pulses.

Peas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Peanuts: IPCC (2006); Table 11.2; Root ratio and belowground N content values are for Root crops, other.

Sugarbeets: IPCC (2006); Table 11.2; values are for Tubers.

Sunflower: IPCC (2006), Table 11.2; values are for Grains.

Sugarcane: combined sources (Wiedenfels 2000, Dua and Sharma 1976; Singels & Bezuidenhout 2002; Stirling et al. 1999; Sitompul et al. 2000).

Tobacco: combined sources (Beyaert 1996; Moustakas and Ntzanis 2005; Crafts-Brandner et al. 1994; Hopkinson 1967; Crafts-Brandner et al. 1987).

Vegetables (Combination of carrots, lettuce/cabbage, melons, onions, peppers and tomatoes):

Carrots: McPharlin et al. (1992); Gibberd et al. (2003); Reid and English (2000); Peach et al. (2000); see IPCC Tubers for R:S and N fraction.

Lettuce, cabbage: combined sources (Huett and Dettman 1991; De Pinheiro Henriques & Marcelis 2000; Huett and Dettman 1989; Peach et al. 2000; Kage et al. 2003; Tan et al. 1999; Kumar et al. 1994; MacLeod et al. 1971; Jacobs et al. 2004; Jacobs et al. 2001; Jacobs et al. 2002); values from IPCC Grains used for N fraction.

Melons: Valantin et al. (1999); squash for R:S; IPCC Grains for N fraction.

Onion: Peach et al. (2000), Halvorson et al. (2002); IPCC (2006) Tubers for N fraction.

Peppers: combined sources (Costa and Gianquinto 2002; Marcussi et al. 2004; Tadesse et al. 1999; Diaz-Perez et al. 2008); IPCC Grains for N fraction.

Tomatoes: Scholberg et al. (2000a,b); Akintoye et al. (2005); values for AGR-N and BGR-N are from Grains.

Table 5-33: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).
[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

To ensure time-series consistency, the same method is applied from 1990 to 2014 for all crops except sugarcane in which the method was applied for 1990 to 2020. For this *Inventory*, new activity data on the burned areas have not been analyzed for 2015 to 2022 for individual crops. The exception is sugarcane in which burned areas have not been analyzed for 2021 to 2022. To complete the emissions time series, a linear extrapolation of the trend is applied to estimate the emissions for the latter part of the time series. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors is used to estimate the trend in emissions over time from 1990 through 2014, and the trend is used to approximate the CH_4, N_2O, CO and NO_x from 2015 to 2022 for all crops except for sugarcane, which was estimated using this method for 2021 to 2022 (Brockwell and Davis 2016). This extrapolation method is consistent with data splicing methods in IPCC (2006). The Tier 2 method described previously will be applied to recalculate the emissions for the latter part of the time series in a future *Inventory*.

Uncertainty

Emissions are estimated using a linear regression model with autoregressive moving-average (ARMA) errors for 2022. The linear regression ARMA model produced estimates of the upper and lower bounds to quantify uncertainty, and the results are summarized in Table 5-34. Methane emissions from field burning of agricultural residues in 2022 are between 0.55 and 0.70 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 11 percent below and 11 percent above the 2022 emission estimate of 0.6 MMT CO_2 Eq. Nitrous oxide emissions are between 0.18 and 0.23 MMT CO_2 Eq., or approximately 13 percent below and 13 percent above the 2022 emission estimate of 0.2 MMT CO_2 Eq.

Table 5-34: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.6	0.55	0.70	-11%	+11%
Field Burning of Agricultural Residues	N_2O	0.2	0.18	0.23	-13%	+13%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Due to data limitations, there are additional uncertainties in agricultural residue burning, particularly the potential omission of burning associated with Kentucky bluegrass (produced on farms for turf grass installation).

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues is implemented with Tier 1 analyses, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process.

Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. An error was identified in the calculation of the emissions using the IPCC (2006) equation after the initial compilation, which was corrected in Box 5.6. An error was also found with the estimation of non-CO_2 emissions from burning of sugarcane residue related to the GWP factors. This error was corrected.

Recalculations Discussion

Recalculations have been conducted for this *Inventory* associated with the addition of residue burning from sugarcane, which was not included in the previous *Inventory*. As a result of this change, CH_4 emissions increased by an annual average of 0.14 MMT CO_2 Eq., or 32 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*. In addition, N_2O emissions increased by an annual average of 0.03 MMT CO_2 Eq., or 21 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key planned improvement is to estimate the emissions associated with field burning of agricultural residues in the states of Alaska and Hawaii. In addition, a method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in several other source categories, including agricultural soil management, cropland remaining cropland, and land converted to cropland chapters of the *Inventory*. The method is based on simulating burning events directly within the DayCent process-based model framework using information derived from remote sensing fire products as described in the Methodology section. This improvement will lead to greater consistency in the methods across sources, ensuring mass balance of carbon and nitrogen in the *Inventory* analysis.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the greenhouse gas fluxes resulting from land use and land-use change in the United States.[1] The Intergovernmental Panel on Climate Change's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between all land use types including: forest land, cropland, grassland, wetlands, and settlements (as well as other land).

The greenhouse gas flux from forest land remaining forest land is reported for all forest ecosystem carbon (C) pools (i.e., aboveground biomass, belowground biomass, dead wood, litter, and mineral and organic soils), harvested wood pools, and non-carbon dioxide (non-CO_2) emissions from forest fires, the application of synthetic nitrogen fertilizers to forest soils, and the draining of organic soils. Fluxes from land converted to forest land are included for aboveground biomass, belowground biomass, dead wood, litter, and carbon stock changes from mineral soils, while carbon stock changes from drained organic soils and all non-CO_2 emissions from land converted to forest land are included in the fluxes from forest land remaining forest land as it is not currently possible to separate these fluxes by conversion category (e.g., grassland converted to forestland).

Fluxes are reported for four agricultural land use/land-use change categories: cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland. The reported greenhouse gas fluxes from these agricultural lands include changes in soil organic carbon stocks in mineral and organic soils due to land use and management, and for the subcategories of forest land converted to cropland and forest land converted to grassland, the changes in aboveground biomass, belowground biomass, dead wood, and litter carbon stocks are also reported. The greenhouse gas flux from grassland remaining grassland also includes estimates of non-CO_2 emissions from grassland fires occurring on both grassland remaining grassland and land converted to grassland.

Fluxes from wetlands remaining wetlands include changes in carbon stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, aboveground and belowground biomass, dead organic matter, soil carbon stock changes and CH_4 emissions from coastal wetlands, as well as N_2O emissions from aquaculture. In addition, CH_4 emissions from reservoirs and other constructed waterbodies are included for the subcategory flooded land remaining flooded land. Estimates for land converted to wetlands include aboveground and belowground biomass, dead organic matter and soil carbon stock changes, and CH_4 emissions from land converted to vegetated coastal wetlands. CO_2 and CH_4 emissions are included for reservoirs and other constructed waterbodies under the subcategory land converted to flooded land. See Section 6.1 for additional information on wetlands included in this *Inventory*.

[1] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux of CO_2 being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Fluxes from settlements remaining settlements include changes in carbon stocks from organic soils, N_2O emissions from nitrogen fertilizer additions to soils, and CO_2 fluxes from settlement trees and landfilled yard trimmings and food scraps. The reported greenhouse gas flux from land converted to settlements includes changes in carbon stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the carbon stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory forest land converted to settlements.

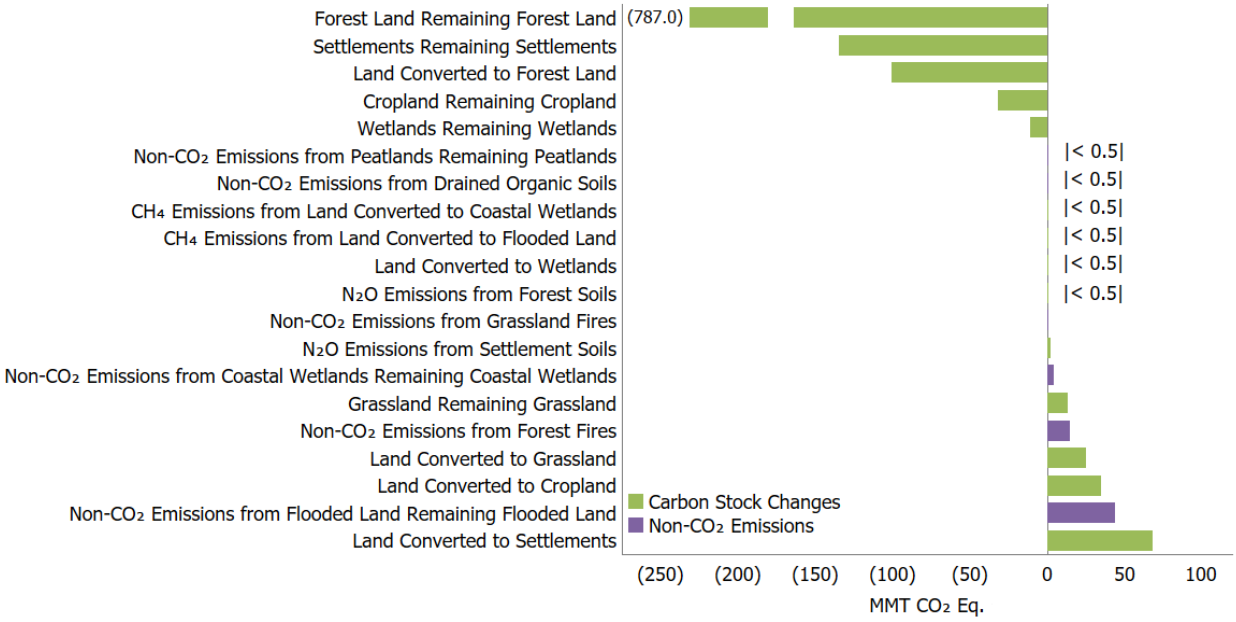
In 2022, the Land Use, Land-Use Change, and Forestry (LULUCF) sector resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 MMT CO_2 Eq.[2] This represents an offset of approximately 14.5 percent of total (i.e., gross) greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 were 58.4 and 9.1 MMT CO_2 Eq., respectively, and combined represent 1.1 percent of total greenhouse gas emissions.[3] In 2022, the overall net flux from LULUCF resulted in a removal of 854.2 MMT CO_2 Eq. Emissions, removals and net greenhouse gas flux from LULUCF are summarized in Figure 6-1 and Table 6-1 by land use and category, and Table 6-2 and Table 6-3 by gas in MMT CO_2 Eq. and kt, respectively. Trends in LULUCF sources and sinks over the 1990 to 2022 time series are shown in Figure 6-2.

Flooded land remaining flooded land was the largest source of non-CO_2 emissions from LULUCF in 2022, accounting for 65.5 percent of the LULUCF sector non-CO_2 emissions. Non-CO_2 emissions from forest fires are the second largest source of LULUCF sector emissions; these emissions have increased 155.2 percent since 1990 and accounted for 21.9 percent of LULUCF non-CO_2 emissions in 2022. Coastal wetlands remaining coastal wetlands and settlements remaining settlements soils accounted for 6.6 and 3.8 percent of non-CO_2 emissions from LULUCF in 2022, respectively, and the remaining sources account for less than one percent each.

[2] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[3] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

Figure 6-1: 2022 LULUCF Chapter Greenhouse Gas Sources and Sinks



Note: Parentheses in horizontal axis indicate net sequestration.

Figure 6-2: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

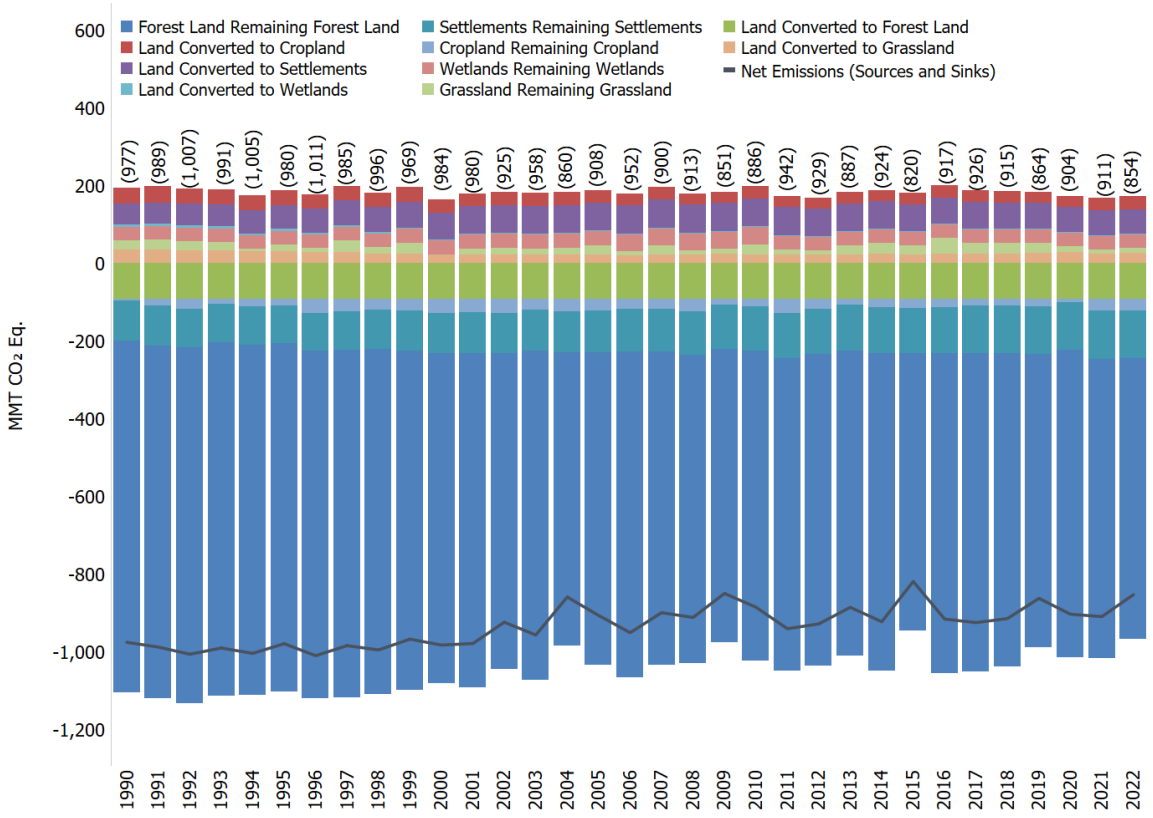


Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Forest Land Remaining Forest Land	**(968.8)**	**(860.0)**	**(863.4)**	**(807.0)**	**(846.3)**	**(823.8)**	**(771.7)**
Changes in Forest Carbon Stocks[a]	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Non-CO_2 Emissions from Forest Fires[b]	5.8	15.5	9.7	5.7	15.3	19.9	14.8
N_2O Emissions from Forest Soils[c]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**
Changes in Forest Carbon Stocks[e]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**
Changes in Mineral and Organic Soil Carbon Stocks	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**
Changes in all Ecosystem Carbon Stocks[f]	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	**24.6**	**24.9**	**29.7**	**28.9**	**17.1**	**11.5**	**14.0**
Changes in Mineral and Organic Soil Carbon Stocks	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.8	1.1	0.3	1.1	0.9	0.6
Land Converted to Grassland	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**
Changes in all Ecosystem Carbon Stocks[f]	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	**36.8**	**39.4**	**38.2**	**38.1**	**38.1**	**38.1**	**38.1**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.6	0.6	0.5	0.6
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(11.1)	(11.1)	(11.1)	(11.1)	(11.1)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
CH_4 Emissions from Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Land Converted to Wetlands	**7.2**	**1.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.6	0.6	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.0)**	**(131.5)**	**(131.8)**	**(132.3)**	**(132.3)**
Changes in Organic Soil Carbon Stocks	9.9	10.1	14.4	14.6	15.1	15.4	15.4
Changes in Settlement Tree Carbon Stocks	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
N_2O Emissions from Settlement Soils[h]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(13.4)	(13.1)	(12.8)	(12.5)	(11.8)
Land Converted to Settlements	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**
Changes in all Ecosystem Carbon Stocks[f]	57.2	77.1	71.4	70.2	68.8	68.2	68.2
LULUCF Emissions[i]	**58.0**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.6**
CH_4	53.1	58.5	55.5	52.5	59.3	62.1	58.4
N_2O	4.8	10.3	7.3	5.5	9.1	10.7	9.1

LULUCF Carbon Stock Change[j]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Sector Net Total[k]	**(976.7)**	**(907.7)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.6)**	**(854.2)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include N_2O emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land-use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[h] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.

[i] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[j] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land-use conversion categories.

[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The carbon stock changes and emissions of CH_4 and N_2O from LULUCF are summarized in Table 6-2 (MMT CO_2 Eq.) and Table 6-3 (kt). Total net carbon sequestration in the LULUCF sector decreased by approximately 10.9 percent between 1990 and 2022. This decrease was primarily due to a decline in the rate of net carbon accumulation in forest land, as well as an increase in emissions from land converted to settlements.[4] Specifically, there was a net carbon accumulation in settlements remaining settlements, which increased from 1990 to 2022, while the net carbon accumulation in forest land remaining forest land and land converted to wetlands slowed over this period. Net carbon accumulation remained steady from 1990 to 2022 in land converted to forest land, cropland remaining cropland, land converted to cropland, and wetlands remaining wetlands, while net carbon accumulation fluctuated in grassland remaining grassland.

Flooded land remaining flooded land was the largest source of CH_4 emissions from LULUCF in 2022, totaling 44.2 MMT CO_2 Eq. (1,579 kt of CH_4). Forest fires resulted in CH_4 emissions of 9.1 MMT CO_2 Eq. (325 kt of CH_4).

For N_2O emissions, forest fires were the largest source from LULUCF in 2022, totaling 5.7 MMT CO_2 Eq. (22 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2022 totaled to 2.5 MMT CO_2 Eq. (10 kt of N_2O). This represents an increase of 22.8 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2022 resulted in N_2O emissions of 0.4 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455.1 percent since 1990, but still account for a relatively small portion of overall emissions.

[4] Carbon sequestration estimates are net figures. The carbon stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the carbon stock decreases, and the pool acts as a source. When gains exceed losses, the carbon stock increases, and the pool acts as a sink; also referred to as net carbon sequestration or removal.

Table 6-2: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
Forest Land Remaining Forest Land	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Land Converted to Forest Land	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Land Converted to Grassland	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	(9.8)	(9.0)	(10.5)	(10.5)	(10.5)	(10.6)	(10.6)
Land Converted to Wetlands	4.1	1.1	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	(111.2)	(118.3)	(133.5)	(134.0)	(134.3)	(134.8)	(134.8)
Land Converted to Settlements	57.2	77.1	71.4	70.2	68.8	68.2	68.2
CH_4	**53.1**	**58.6**	**55.6**	**52.5**	**59.3**	**62.2**	**58.4**
Forest Land Remaining Forest Land: Forest Fires[b]	3.4	9.2	6.0	3.4	9.8	12.7	9.1
Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.6	0.2	0.6	0.5	0.3
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Land Converted to Wetlands: Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
N_2O	**4.8**	**10.4**	**7.2**	**5.5**	**9.1**	**10.8**	**9.1**
Forest Land Remaining Forest Land: Forest Fires[b]	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Forest Land Remaining Forest Land: Forest Soils[e]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land Remaining Forest Land: Drained Organic Soils[c]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.5	0.1	0.5	0.4	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[f]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
LULUCF Carbon Stock Change[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Emissions[g]	**57.9**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.5**
LULUCF Sector Net Total[h]	**(976.7)**	**(907.6)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.5)**	**(854.3)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining

settlements, and land converted to settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[e] Estimates include N_2O emissions from nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from flooded land remaining flooded land, land converted to flooded land, and land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[h] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-3: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(1,034,678)**	**(976,578)**	**(978,287)**	**(921,607)**	**(972,765)**	**(983,418)**	**(921,792)**
Forest Land Remaining Forest Land	(974,778)	(876,001)	(873,508)	(813,183)	(862,033)	(844,194)	(787,006)
Land Converted to Forest Land	(100,216)	(100,151)	(100,409)	(100,284)	(100,297)	(100,305)	(100,294)
Cropland Remaining Cropland	(5,042)	(31,622)	(17,786)	(19,418)	(8,819)	(31,970)	(31,710)
Land Converted to Cropland	45,403	34,501	31,936	31,376	29,297	34,893	35,110
Grassland Remaining Grassland	24,366	24,071	28,557	28,536	16,086	10,566	13,352
Land Converted to Grassland	35,255	21,792	25,178	25,404	28,696	24,542	25,621
Wetlands Remaining Wetlands	(9,770)	(8,984)	(10,469)	(10,509)	(10,535)	(10,582)	(10,559)
Land Converted to Wetlands	4063	1069	304	309	305	309	313
Settlements Remaining Settlements	(111,203)	(118,335)	(133,464)	(134,000)	(134,301)	(134,842)	(134,812)
Land Converted to Settlements	57,242	77,081	71,373	70,161	68,836	68,165	68,195
CH_4	**1,898**	**2,091**	**1,983**	**1,875**	**2,118**	**2,218**	**2,087**
Forest Land Remaining Forest Land: Forest Fires[b]	122	328	213	120	349	452	327
Forest Land Remaining Forest Land: Drained Organic Soils[c]	1	1	1	1	1	1	1
Grassland Remaining Grassland: Grassland Fires[d]	4	15	22	6	20	18	12
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	1,509	1,569	1,578	1,579	1,579	1,579	1,579
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	149	151	153	153	154	154	154
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	102	16	8	8	8	8	8
Land Converted to Wetlands: Land Converted to Coastal Wetlands	10	10	7	7	7	6	6
N_2O	**18**	**39**	**27**	**21**	**34**	**41**	**34**
Forest Land Remaining Forest Land: Forest Fires[b]	9	24	14	9	21	27	21
Forest Land Remaining Forest Land: Forest Soils[e]	+	2	2	2	2	2	2

Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[d]	+	1	2	1	2	2	1
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	1	1	1	1	1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[f]	8	12	9	9	9	10	10

+ Absolute value does not exceed 0.5 kt.

[a] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[e] Estimates include N_2O emissions from nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Each year, some emission and sink estimates in the LULUCF sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emissions and removals estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to ensure that the trend is accurate. Of the updates implemented for this *Inventory*, the most significant include (1) managed forest land in Hawaii and several U.S. Territories[5] were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory;* (2) updated methodological framework and accounting of carbon in structural components of trees across the United States for total tree cubic-foot volume, biomass, and carbon which led to an increase in estimated forest carbon stocks; and (3) incorporating new U.S. Department of Agriculture (USDA) National Resources Inventory (NRI) data through 2017, incorporating USDA-Natural Resources Conservation Service (NRCS) Conservation Effects Assessment Program (CEAP) survey data for 2013 to 2016, incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020, in addition to other methodological updates for the estimation of croplands and grasslands described further in those respective category sections. Together, these and other updates increased total carbon sequestration estimates by an average of 133.6 MMT CO_2 Eq. (15.5 percent) and decreased total non-CO_2 emissions by 2.2 MMT CO_2 Eq. (2.6 percent) across the time series, compared to the previous *Inventory* (i.e., 1990 to 2021). For more information on specific methodological updates, please see the Recalculations Discussion within the respective category section of this chapter.

Emissions and removals reported in the LULUCF chapter include those from all states; however, for Hawaii and Alaska some emissions and removals from land use and land-use change are not included in most cases (see chapter sections on Uncertainty and Planned Improvements for more details). In addition, U.S. Territories are not included for most categories. EPA continues to review available data on an ongoing basis to include emissions and

[5] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

removals from U.S. Territories in future *Inventories* to the extent they are occurring (e.g., see Box 6-2). See Annex 5 for more information on EPA's assessment of the emissions and removals not included in this *Inventory*.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the gross emissions total presented in this report for the United States excludes emissions and removals from LULUCF. The LULUCF Sector Net Total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals estimates are calculated using internationally accepted methods in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines), 2013 Supplement to the 2006 IPCC Guidelines for National GHG Inventories: Wetlands,* and the *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC.[6] The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the Land Use Land-Use Change and Forestry chapter does not preclude alternative examinations. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follow this common format, and provides an explanation of the application of methods used to calculate emissions and removals.

6.1 Representation of the U.S. Land Base

A national land use representation system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the *Inventory* time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-4), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-5), and (3) account for greenhouse gas fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (see IPCC (2010), Ogle et al. (2018) for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. This section of the *Inventory* has been developed in order to comply with this guidance. While the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) provide guidance for factoring out natural emissions and removals, the United States does not apply this guidance and estimates all emissions/removals on managed land regardless of whether the driver was natural.

[6] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Three databases are used to track land management in the United States and are used as the basis to classify United States land area into the thirty-six IPCC land use and land-use change categories (Table 6-5) (IPCC 2006). The three primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI),[7] the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[8] Database, and the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD).[9] See Table 6-6 for an overview of the land area databases used to characterize land use in federal and non-federal lands in the conterminous United States, Alaska, and Hawaii.

The total land area included in the United States *Inventory* is 936 million hectares across the 50 states.[10] Approximately 886 million hectares of this land base is considered *managed* and 50 million hectares is *unmanaged*, a distribution that has remained stable over the time series of the *Inventory* (Table 6-5). In 2022, the United States had a total of 281 million hectares of managed forest land (0.47 percent decrease compared to 1990). There are 160 million hectares of cropland (8.3 percent decrease compared to 1990), 339 million hectares of managed grassland (0.35 percent increase compared to 1990), 39 million hectares of managed wetlands (3 percent increase compared to 1990), 47 million hectares of settlements (41 percent increase compared to 1990), and 21 million hectares of managed other land (1.2 percent decrease compared to 1990) (Table 6-5).

Wetlands are not differentiated between managed and unmanaged with the exception of remote areas in Alaska, and so are classified and reported mostly as managed land within the coterminous United States.[11] In addition, carbon stock changes are not currently estimated for the entire managed land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the *Inventory* (e.g., grassland remaining grassland within interior Alaska).[12,13] Planned improvements are under development to estimate carbon stock changes and greenhouse gas emissions on all managed land and to ensure consistency between the total area of managed land in the land-representation description and the remainder of the *Inventory*.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement and economic patterns (Figure 6-3). Forest land tends to be more common in the eastern United States, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper

[7] NRI data are available at https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[8] FIA data are available at https://www.fia.fs.usda.gov/tools-data/index.php.

[9] NLCD data are available at http://www.mrlc.gov/ and MRLC is a consortium of several U.S. government agencies.

[10] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future *Inventories*. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2.

[11] According to the IPCC (2006), wetlands are considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Alaska is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. As a result, all wetlands in the conterminous United States and Hawaii are reported as managed in the land representation, but emission/removal estimates only developed for those wetlands that are included under the flooded lands, coastal wetlands or peat extraction categories. Efforts are underway to better reflect wetland estimates in the future *Inventories*. See the Planned Improvements section of the *Inventory* for future refinements to the wetland area estimates.

[12] Other discrepancies occur because the coastal wetlands analysis is based on another land use product (NOAA C-CAP) that is not currently incorporated into the land representation analysis for this section, which relies on the NRI and NLCD for wetland areas. EPA anticipates addressing these discrepancies in future *Inventories*.

[13] These "managed area" discrepancies also occur in the Common Reporting Tables (CRTs) submitted to the UNFCCC.

Midwest and eastern portions of the country, as well as coastal regions. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-4: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land Use Categories	1990	2005	2018	2019	2020	2021	2022
Managed Lands	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**
Forest	282,375	281,806	280,971	280,440	281,067	281,071	281,041
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	337,867	340,022	338,927	339,801	339,562	339,260	339,048
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	37,456	38,310	38,495	38,551	38,430	38,478	38,566
Other	20,911	20,588	20,773	20,734	20,718	20,682	20,657
Unmanaged Lands	**49,708**	**49,711**	**49,710**	**49,710**	**49,710**	**49,710**	**49,710**
Forest	9,766	9,782	9,814	9,815	9,817	9,818	9,819
Croplands	0	0	0	0	0	0	0
Grasslands	25,090	25,154	25,268	25,266	25,265	25,264	25,262
Settlements	0	0	0	0	0	0	0
Wetlands	4,118	4,057	3,936	3,935	3,935	3,935	3,936
Other	10,734	10,718	10,693	10,693	10,693	10,693	10,693
Total Land Areas	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**
Forest	292,140	291,588	290,784	290,255	290,883	290,889	290,861
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	362,957	365,176	364,195	365,068	364,827	364,524	364,310
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	41,574	42,366	42,430	42,486	42,365	42,413	42,502
Other	31,645	31,306	31,466	31,428	31,411	31,375	31,350

Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

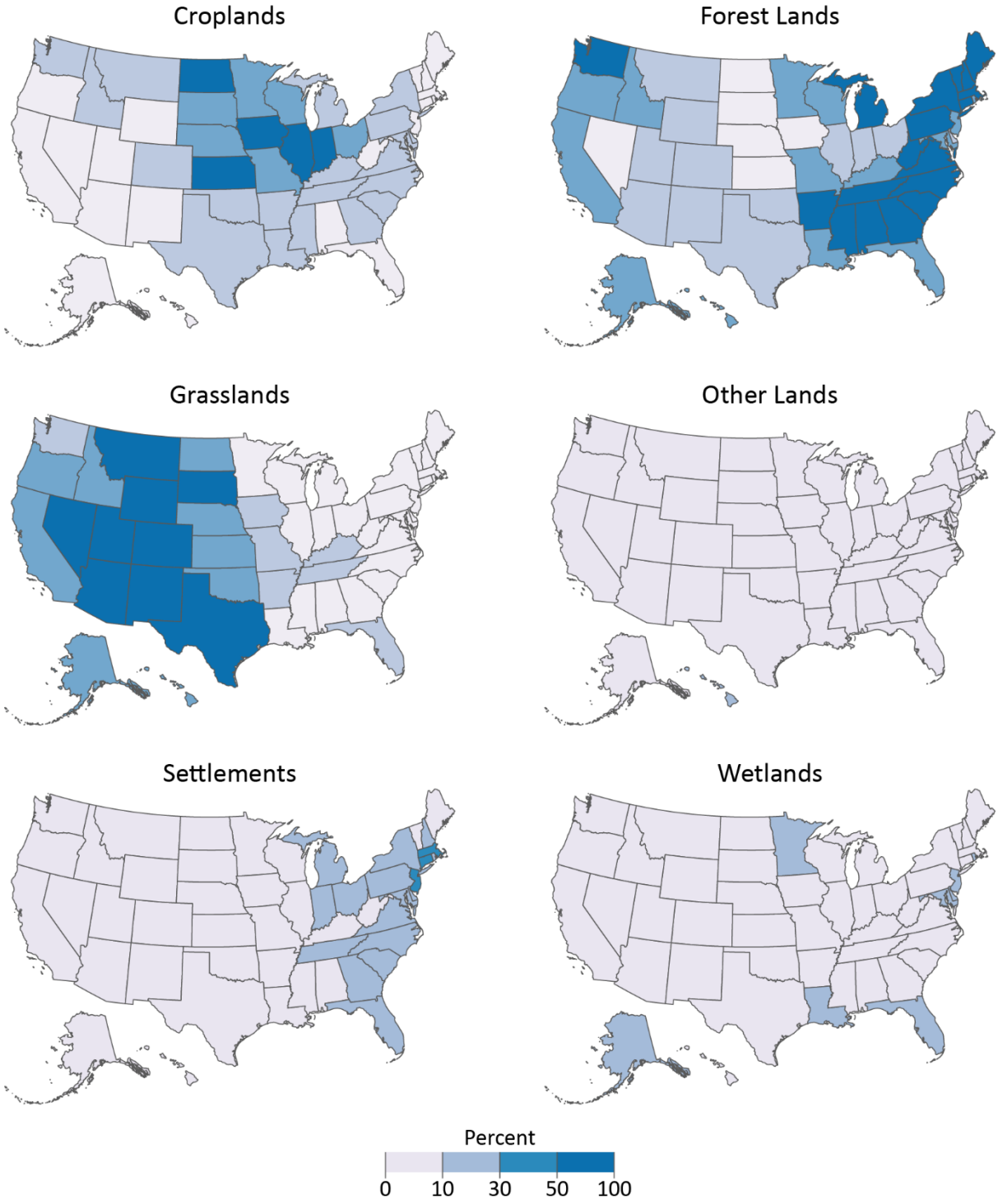
Land Use & Land-Use Change Categories[a]	1990	2005	2018	2019	2020	2021	2022
Total Forest Land	**282,375**	**281,806**	**280,971**	**280,440**	**281,067**	**281,071**	**281,041**
FF	281,290	280,587	279,683	279,167	279,818	279,829	279,802
CF	208	137	101	88	77	77	76
GF	775	968	1,038	1,048	1,036	1,037	1,040
WF	15	23	21	18	16	15	15
SF	11	18	20	21	20	19	20
OF	77	73	108	98	99	94	89
Total Cropland	**174,498**	**165,632**	**161,394**	**160,693**	**160,112**	**160,079**	**160,033**
CC	162,273	150,417	149,721	149,503	149,823	150,591	151,276
FC	173	77	63	64	60	63	65
GC	11,673	14,623	11,231	10,758	9,914	9,132	8,418
WC	119	178	99	98	86	81	75
SC	75	102	107	105	101	97	94
OC	186	235	173	166	129	115	107
Total Grassland	**337,867**	**340,022**	**338,927**	**339,801**	**339,562**	**339,260**	**339,048**
GG	328,566	315,931	318,960	320,255	320,856	321,910	322,779
FG	572	1,663	4,184	4,202	4,177	4,162	3,894
CG	8,177	17,746	13,594	13,491	13,205	12,200	11,444
WG	168	466	181	172	159	143	134
SG	43	525	230	190	139	100	93
OG	341	3,692	1,778	1,491	1,026	746	705
Total Wetlands	**37,456**	**38,310**	**38,495**	**38,551**	**38,430**	**38,478**	**38,566**

WW	36,900	36,288	37,236	37,425	37,448	37,626	37,783
FW	37	71	96	85	83	78	76
CW	145	637	362	310	261	221	187
GW	326	1,169	564	501	415	342	314
SW	0	38	17	14	10	2	2
OW	47	107	220	216	212	210	204
Total Settlements	**33,427**	**40,172**	**45,971**	**46,312**	**46,641**	**46,960**	**47,185**
SS	30,562	31,445	40,769	41,615	42,466	43,189	43,748
FS	301	466	468	455	448	446	440
CS	1,231	3,604	1,917	1,726	1,528	1,366	1,228
GS	1,276	4,371	2,630	2,349	2,062	1,830	1,648
WS	4	59	30	25	18	14	14
OS	54	229	157	141	120	115	108
Total Other Land	**20,911**	**20,588**	**20,773**	**20,734**	**20,718**	**20,682**	**20,657**
OO	20,177	17,022	18,050	18,293	18,553	18,805	18,874
FO	51	77	98	101	101	108	111
CO	287	603	629	582	540	489	444
GO	371	2,764	1,772	1,541	1,309	1,068	1,018
WO	22	100	206	206	205	204	200
SO	2	21	17	11	10	10	10
Grand Total	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**

[a] The abbreviations are "F" for forest land, "C" for cropland, "G" for grassland, "W" for wetlands, "S" for settlements, and "O" for other lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "FF" is forest land remaining forest land), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "CF" is Cropland Converted to Forest Land).

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for wetlands, which based on the definitions for the current U.S. Land Representation assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include U.S. Territories in future *Inventories*. In addition, carbon stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the *Inventory* (see land use chapters e.g., Forest Land Remaining Forest Land for more information). Totals may not sum due to independent rounding.

Figure 6-3: Percent of Total Land Area for Each State in the General Land Use Categories for 2022



Methodology and Time-Series Consistency

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land use category, but does not provide detailed information on transfer of land area between categories following land-use change and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., forest land converted to cropland, cropland converted to forest land, and grassland converted to cropland), using survey samples or other forms of data, but does not provide spatially-explicit location data. Approach 3 extends Approach 2 by providing spatially-explicit location data, such as surveys with spatially identified sample locations and maps obtained from remote sensing products. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI, FIA and NLCD are Approach 3 data sources that provide spatially-explicit representations of land use and land-use conversions. Lands are treated as remaining in the same category (e.g., cropland remaining cropland) if a land-use change has not occurred in the last 20 years, consistent with the IPCC guidelines (2006). Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., cropland converted to forest land).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the general definition of managed land provided by the IPCC (2006), but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society.[14]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

[14] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management or origin (i.e., constructed rather than natural origin). Therefore, unless wetlands are converted into cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, most wetlands are reported as managed with the exception of wetlands in remote areas of Alaska, but emissions from managed wetlands are only reported for coastal regions, flooded lands (e.g., reservoirs) and peatlands where peat extraction occurs due to insufficient activity data to estimate emissions and limited resources to improve the *Inventory*. See the Planned Improvements section of the *Inventory* for future refinements to the wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[15]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on carbon stocks.[16] Unmanaged land is also re-classified as managed over time if anthropogenic activity is introduced into the area based on the definition of managed land.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: forest land, cropland, grassland, wetlands, settlements and other land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of forest land is based on the FIA definition of forest,[17] while definitions of cropland, grassland, and settlements are based on the NRI.[18] The definitions for other land and wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one acre (0.4 hectare) in size with at least ten percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 m) at maturity in situ. Forest land includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands, that have at least ten percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 m) wide or an acre (0.4 ha) in size. However, land is not classified as forest land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for forest land. These areas are classified as settlements. In addition, forest land does not include land that is predominantly under an agricultural land use (Nelson et al. 2020).
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[19] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for forest land. Lands in temporary fallow or

[15] There are some areas, such as forest land and grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[16] There are examples of managed land transitioning to unmanaged land in the United States. For example, in 2018, 100 hectares of managed grassland converted to unmanaged because data indicated that no further grazing occurred. Livestock data are collected annually by the Department of Agriculture, and no livestock had occurred in the area since the mid-1970s, and therefore there was no longer active management through livestock grazing. The area is also remote, at least 10 miles from roads and settlements, and therefore the land was no longer managed based on the implementation criteria.

17 See https://www.fia.fs.usda.gov/library/field-guides-methods-proc/docs/2022/core_ver9-2_9_2022_SW_HW%20table.pdf, page 23.

[18] See https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[19] Currently, there is no data source to account for biomass carbon stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the cropland land base.

enrolled in conservation reserve programs (i.e., set-asides[20]) are also classified as cropland, as long as these areas do not meet the forest land criteria. Roads through cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from cropland area estimates and are, instead, classified as settlements.

- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Land is also categorized as grassland if there have been three or fewer years of continuous hay production.[21] Savannas, deserts, and tundra are considered grassland. Drained wetlands are considered grassland if the dominant vegetation meets the plant cover criteria for grassland. Woody plant communities of low forbs, shrubs and woodlands, such as sagebrush, mesquite, chaparral, mountain shrubland, and pinyon-juniper, are also classified as grassland if they do not meet the criteria for forest land. Grassland includes land managed with agroforestry practices, such as silvopasture and windbreaks, if the land is principally grass, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for forest land. Roads through grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from grassland and are, instead, classified as settlements.
- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to lakes, reservoirs, and rivers. In addition, all coastal wetlands are considered managed regardless of whether the water level is changed or if they were created by human activity. Certain areas that fall under the managed wetlands definition are included in other land uses based on the IPCC guidance and national circumstances, including lands that are flooded for most or just part of the year in croplands (e.g., rice cultivation and cranberry production), grasslands (e.g., wet meadows dominated by grass cover) and forest lands (e.g., riparian forests near waterways). See Section 6.8 for more information.
- *Settlements*: A land-use category representing developed areas consisting of units equal to or greater than 0.25 acres (0.1 ha) that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are all tracts that may meet the definition of forest land, and tracts of less than ten acres (4.05 ha) that may meet the definitions for cropland, grassland, or other land but are completely surrounded by urban or built-up land, and so are included in the settlements category. Rural transportation corridors located within other land uses (e.g., forest land, cropland, and grassland) are also included in settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories. Following the guidance provided by the IPCC (2006), carbon stock changes and non-CO_2 emissions are not estimated for other lands because these areas are largely devoid of biomass, litter and soil carbon pools. However, carbon stock changes and non-CO_2 emissions should be estimated for land converted to other land during the first 20 years following conversion to account for legacy effects.

[20] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees, but is still classified as cropland based on national circumstances.

[21] Areas with four or more years of continuous hay production are cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices. Occasional harvest of hay from grasslands typically does not involve cultivation or other intensive management practices.

Land Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land Use Data Sources

The three main sources for land use data in the United States are the NRI, FIA, and the NLCD (Table 6-6). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because these surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate carbon stock changes, N_2O, and CH_4 emissions on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use. Sources of land use data included in the land representation in this *Inventory* are consistent with those included in the previous *Inventory.*

Table 6-6: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

	NRI	FIA	NLCD
Forest Land			
Conterminous United States			
Non-Federal		•	
Federal		•	
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal		•	
Federal		•	
Croplands, Grasslands, Other Lands, Settlements, and Wetlands			
Conterminous United States			
Non-Federal	•		
Federal			•
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal			•
Federal			•

National Resources Inventory

For the *Inventory*, the NRI is the official source of data for land use and land-use change on non-federal lands in the conterminous United States and Hawaii, and is also used to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land use information (Nusser and Goebel 1997). The NRI survey utilizes data obtained from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands and grasslands (i.e., agricultural lands), and is used as the

basis to account for carbon stock changes in agricultural lands (except federal grasslands). The NRI survey was conducted every five years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period (note: most of the data have the same land use at the beginning and end of the five-year periods). If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land use data for non-federal lands in the conterminous United States and Hawaii. This *Inventory* incorporates data through 2017 from the NRI. The land use patterns are assumed to remain the same from 2018 through 2022 for this *Inventory*, but the time series will be updated when new data are integrated into the land representation analysis.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is the official source of data on forest land area and management data for the *Inventory* and is another statistically-based survey for the United States. The Forest Inventory and Analysis engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for each consecutive phase are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate carbon stock changes for forest land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to ten years. A new national plot design and annual sampling design was introduced by the FIA program in 1998 and is now used in all states. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five to seven years in the eastern United States and once every ten years in the western United States. See Annex 3.13 for the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2019 through 2022; see Table A-202 in Annex 3.13).

National Land Cover Dataset

As noted above, while the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. Gaps exist in the land representation when the NRI and FIA datasets are combined, such as federal grasslands operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[22] The NLCD is used to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska with the exception of forest lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2004, 2006, 2008, 2011, 2013, 2016, 2019, and 2021 in the conterminous United States (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015, Dewitz, 2023), and also for Alaska in 2001, 2011, and 2016 and Hawaii in 2001. Note that the 2021 NLCD product was not available at the time the land representation was begun for this *Inventory* so it was not included. A NLCD change product is not available for Hawaii because data are only available for one year, i.e., 2001. The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30-meter resolution, and the land-cover categories have been aggregated into the 36 IPCC land-use categories for the conterminous United States and Alaska, and into the six IPCC land-use categories for Hawaii. The land-use patterns are assumed to remain the same after the last year of

[22] The NRI survey program does not include U.S. Territories with the exception of non-federal lands in Puerto Rico. The FIA program recently began implementing surveys of forest land in U.S. Territories and those data will be used in the years ahead. Furthermore, NLCD does not include coverage for all U.S. Territories.

data in the time series, which is 2001 for Hawaii, 2019 for the conterminous United States and 2016 for Alaska, but the time series will be updated when new data are released.

For the conterminous United States, the aggregated maps of IPCC land-use categories obtained from the NLCD products were used in combination with the NRI database to represent land use and land-use change for federal lands, with the exception of forest lands, which are based on FIA. Specifically, NRI survey locations designated as federal lands were assigned a land use/land-use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location in the NRI). The sources of these additional data are discussed in subsequent sections of the report.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. The following criteria are used in order to apply the definition in an analysis of managed land:

- All croplands and settlements are designated as managed so only grassland, forest land, wetlands or other lands may be designated as unmanaged land;[23]
- All forest lands with active fire protection are considered managed;
- All forest lands designated for timber harvests are considered managed;
- All grasslands are considered managed at a county scale if there are grazing livestock in the county;
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;
- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and/or private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged remain in the managed land base for 20 years following the conversion to account for legacy effects of management on carbon stocks.

The analysis of managed lands, based on the criteria listed above, is conducted using a geographic information system (Ogle et al. 2018). Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Forest lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. In addition, forest lands with timber harvests are designated as managed based on county-level estimates of timber products in the U.S. Forest Service Timber Products Output Reports (U.S. Department of Agriculture 2012). Timber harvest data lead to additional designation of managed forest land in Alaska. The designation of grasslands as managed is based on grazing livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2015). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD.

Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed

[23] All wetlands are considered managed in this *Inventory* with the exception of remote areas in Alaska. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Hawaii is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. Regardless, a planned improvement is underway to subdivide managed and unmanaged wetlands.

that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance (e.g., forest lands with active fire protection). Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base.

Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and *Coal Production and Preparation Report* (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of disturbance to the landscape for approximately 130 petroleum extraction sites and 223 mines. After applying the criteria identified above, the resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands in Alaska. The remaining land represents the unmanaged land base. The resulting spatial product is also used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii.[24]

Approach for Combining Data Sources

The managed land base in the United States has been classified into the 36 IPCC land use/land-use conversion categories (Table 6-5) using definitions developed to meet national circumstances, while adhering to IPCC guidelines (2006).[25] In practice, the land was initially classified into land-use subcategories within the NRI, FIA, and NLCD datasets, and then aggregated into the 36 broad land use and land-use change categories identified in IPCC (2006).

All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for forest land. Therefore, another step in the analysis is to address the inconsistencies in the representation of the forest land among the three databases. NRI and FIA have different criteria for classifying forest land in addition to different sampling designs, leading to discrepancies in the resulting estimates of forest land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying forest land on federal lands. Any change in forest land area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the forest land area and the amount of land designated as other land uses, such as the amount of grassland, cropland, and wetlands (i.e., areas for the individual land uses must sum to the total managed land area of the country).

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of forest land in the conterminous United States. Adjustments are made in the forest land remaining forest land, land converted to forest land, and forest land converted to other uses (i.e., grassland, cropland, settlements, other lands, and wetlands). All adjustments are made at the state scale to address the discrepancies in areas associated with forest land and conversions to and from forest land. There are three steps in this process. The first step involves adjustments to land converted to forest land (grassland, cropland, settlements, other lands, and wetlands), followed by a second step in which there are adjustments in forest land converted to another land use (i.e., grassland, cropland, settlements, other lands, and wetlands), and the last step is to adjust forest land remaining forest land.

In the first step, land converted to forest land in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal land converted to forest land, respectively. FIA data have not provided

[24] The exception is cropland and settlement areas in the NRI, which are classified as managed, regardless of the managed land base obtained from the spatial analysis described in this section.

[25] Definitions are provided in the previous section.

specific land-use categories that are converted to forest land in the past, but rather a sum of all land converted to forest land.[26] The NRI and NLCD provide information on specific land-use conversions, such as grassland converted to forest land. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of specific land-use conversions into forest land for the state, prior to any further adjustments. For example, if 50 percent of the land-use change to forest land is associated with grassland converted to forest land in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of land converted to forest land is addressed by increasing or decreasing the area in grassland converted to forest land. Moreover, any increase or decrease in grassland converted to forest land in NRI or NLCD is addressed by a corresponding change in the area of grassland remaining grassland, so that the total amount of managed area is not changed within an individual state. Since the sum of all land converted to forest land is used to adjust specific land-use conversions into forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where specific land-use conversions into forest land do not exist in the FIA data.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for forest land converted to other uses. Similar to land converted to forest land, FIA have not provided information on the specific land-use changes in the past,[27] so areas associated with forest land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount of area in each conversion class in these datasets. Since the sum of all forest land converted to other uses is used to adjust specific land-used conversions out of forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where a specific land-use conversion out of forest land does not exist in the FIA data.

In the final step, the area of forest land remaining forest land in each state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in forest land remaining forest land is associated with less-precise estimates of grassland remaining grassland and wetlands remaining wetlands in the NRI and NLCD. This step also assumes that there are no changes in the land-use conversion categories. Therefore, corresponding adjustments are made in the area estimates of grassland remaining grassland and wetlands remaining wetlands from the NRI and NLCD. This adjustment balances the change in forest land remaining forest land area, which ensures no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level according to NRI and NLCD (i.e., a higher proportion of grassland led to a larger adjustment in grassland area).

The modified NRI data are then aggregated to provide the land use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based on the NLCD data after adjusting this dataset to be consistent with forest land areas in the FIA (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Land representation for both non-federal and federal forest lands in the conterminous United States and Alaska are based on the FIA. The FIA is used as the basis for both forest land area data as well as to estimate carbon stocks and fluxes on forest land in the conterminous United States and Alaska. The FIA does have survey plots in Alaska that are used to determine the carbon stock changes, and the associated area data for this region are harmonized with NLCD using the methods described above. NRI is used in the current report to provide forest land areas on non-federal lands in Hawaii, and NLCD is

[26] The FIA program has started to collect data on the specific land uses that are converted to forest land, which will be further investigated and incorporated into a future *Inventory*.

[27] The FIA program has started to collect data on the specific land uses following conversion from forest land, which will be further investigated and incorporated into a future *Inventory*.

used for federal lands. In Hawaii and the U.S. Territories, FIA data are being collected; these data were used to compile area estimates and emissions and removals for forest land in this *Inventory*.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. The NRI is used as the basis for both cropland area data as well as to estimate soil carbon stocks and fluxes on cropland. The NLCD is used to determine cropland area and soil carbon stock changes on federal lands in the conterminous United States and Hawaii. The NLCD is also used to determine croplands in Alaska, but carbon stock changes are not estimated for this region in the current *Inventory*.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. The NRI is used as the basis for both grassland area data as well as to estimate soil carbon stocks and non-CO_2 greenhouse emissions on grassland. Grassland area and soil carbon stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. The NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal grasslands in Hawaii, but the current *Inventory* does not include carbon stock changes in these areas.
- *Wetlands*: The NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while the land representation data for federal wetlands and wetlands in Alaska are based on the NLCD.[28]
- *Settlements*: The NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of forest land or grassland under ten acres (4.05 ha) are contained within settlements or urban areas, they are classified as settlements (urban) in the NRI database. If these parcels exceed the ten-acre (4.05 ha) threshold and are grassland, they are classified as grassland by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Land representation for settlements on federal lands and Alaska is based on the NLCD.
- *Other Land*: Any land that is not classified into one of the previous five land-use categories is categorized as other land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority based on the following order:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as grassland, forest land, wetlands, and cropland, respectively, but when located in close proximity to settlement areas, they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture are classified as cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as cropland, even though these areas may also meet the definitions of grassland or forest land, respectively. Similarly, wetlands are considered croplands if they are used for crop production, such as rice or cranberries. Forest land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards)

[28] This analysis does not distinguish between managed and unmanaged wetlands except for remote areas in Alaska, but there is a planned improvement to subdivide managed and unmanaged wetlands for the entire land base.

or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while wetlands and then other land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land-use category. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as forest land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as cropland if they are used for crop production, such as rice, or as grassland if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions and removals from these areas should be included in the *Inventory* if the land is considered managed, and therefore impacted by anthropogenic activity in accordance with the guidance provided by the IPCC (2006).

QA/QC and Verification

The land base obtained from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) Survey (U.S. Census Bureau 2010). The United States Census Bureau gathers data on the population and economy and has a database of land areas for the country. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are obtained from remote sensing data instead of the land survey approach used by the United States Census Survey. The Census does not provide a time series of land-use change data or land management information, which is needed for estimating greenhouse gas emissions from land use and land-use change. Regardless, the Census does provide sufficient information to provide a quality assurance check on the *Inventory* data. There are 46 million more hectares of land in the United States according to the Census, compared to the total area estimate of 936 million hectares obtained from the combined NRI, FIA, and NLCD data, a 4.8 percent difference. Much of this difference is associated with open water in coastal regions and the Great Lakes, which is included in the TIGER Survey of the Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4 percent difference when open water in coastal regions is removed from the TIGER data. General QC procedures for data gathering and data documentation also were applied consistent with the QA/QC and Verification Procedures described in Annex 8.

Recalculations Discussion

The land representation estimates were recalculated from the previous *Inventory* with the following datasets: a) updated FIA data from 1990 to 2022 for the conterminous United States and Alaska, b) NRI data from 1990 to 2017 for the conterminous United States and Hawaii, and c) NLCD data for the conterminous United States from 2001 through 2019 and Alaska from 2001 through 2016. There were several changes in methods that resulted in small changes between this *Inventory* and the previous *Inventory*. First, pasture land was previously classified as cropland in the compilation of forest land conversion estimates using FIA data and is now classified as grassland to align with methods and definitions used to classify grasslands using NRI data. This led to a decrease in total managed cropland area and an increase in grassland area. Second, FIA data are now used to classify forest land and conversions to and from forest land in coastal southeast and southcentral Alaska which resulted in minor changes, primarily between forest land, wetlands, and grasslands, between this *Inventory* and the previous *Inventory*. Lastly, methods for classifying wetlands using FIA data were refined so that all water bodies are now classified as wetlands (previously some water bodies were classified as other lands) aligning with methods and definitions in the NRI. Collectively, these refinements in FIA methods to better align with methods for the other data sources (i.e., NRI and NLCD) resulted in changes throughout the entire representation of land (see "Approach for Combining Data Sources"). Specifically, managed wetland area decreased, on average over the time series, by 1.2 percent. Grassland and forest land increased by 0.1 percent and 0.04 percent, respectively. Settlement area decreased by 0.05 percent and cropland and managed other lands were essentially unchanged in the latest *Inventory*.

Planned Improvements

Research is underway to harmonize NRI and FIA sampling frames to improve consistency and facilitate estimation using multi-frame sampling. This includes development of a common land use classification schema between the two land inventories that can be used in the harmonization process. These steps will allow for population estimation exclusive of auxiliary information (e.g., NLCD). The multi-frame sample will also serve as reference data for the development of spatially explicit and spatially continuous map products for each year in the *Inventory* time series. Another key planned improvement for the *Inventory* is to fully incorporate area data by land-use type for U.S. Territories. Although most of the managed land in the United States is included in the current land use data for the conterminous United States, Alaska, and Hawaii, a complete reporting of all lands in the United States, including U.S. Territories, is a key goal for the near future. An initial assessment of data sources for land use area data for U.S. Territories by land-use category are provided in Box 6-2. In addition, this *Inventory* includes forest land areas estimated for American Samoa, Guam, Hawaii, Northern Marianas Islands, U.S. Virgin Islands, and Puerto Rico using periodic inventories from the FIA program. These estimates are included in the forest land category, and the methods for compiling these area estimates and the associated carbon stocks and fluxes and integration of these estimates into the land representation will be refined to compensate for data limitations in the time series while also taking advantage of new data and data products. See Box 6-2.

Box 6-2: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land-cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis Program, Caribbean Land Cover project, National Land Cover Dataset (NLCD), USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). Land-cover data can be used to inform a land use classification if there is a time series to evaluate the dominant practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national *Inventory* as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the *Inventory*. Recommendations are to use the NOAA C-CAP Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico, so the NLCD was used for this area. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States (see Table 6-7).

Table 6-7: Total Land Area (Hectares) by Land Use Category for U.S. Territories

	Puerto Rico	U.S. Virgin Islands	Guam	Northern Marianas Islands	American Samoa	Total
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Note: Totals may not sum due to independent rounding.

Methods in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) have been applied to estimate emissions and removals from coastal wetlands. Specifically, greenhouse gas emissions from coastal wetlands have been developed for the *Inventory* using the NOAA C-CAP land-cover product. The NOAA C-CAP product is not used directly in the land representation analysis, however, so a planned improvement for future Inventories is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI, FIA and NLCD. Estimates from flooded lands are also included in this *Inventory*, but data are not directly used in the land representation analysis at this time; this is a planned improvement to include for future inventories. In addition, the current *Inventory* does not include a classification of managed and unmanaged wetlands, except for remote areas in Alaska. Consequently, there is a planned improvement to classify managed and unmanaged wetlands for the conterminous United States and Hawaii, and more detailed wetlands datasets will be evaluated and integrated into the analysis to meet this objective.

6.2 Forest Land Remaining Forest Land (CRT Category 4A1)

Changes in Forest Carbon Stocks (CRT Category 4A1)

Delineation of Carbon Pools

For estimating carbon stocks or stock change (flux), carbon in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 millimeters (mm) diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes all duff, humus, and fine woody debris above the mineral soil as well as woody fragments with diameters of up to 7.5 cm.
- Soil organic carbon (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools. Organic (e.g., peat and muck) soils have a minimum of 12 to 20 percent organic matter by mass and develop under poorly drained conditions of wetlands. All other soils are classified as mineral soil types and typically have relatively low amounts of organic matter.

In addition, there are two harvested wood pools included when estimating carbon flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined carbon storage pools and the atmosphere as a result of biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, carbon is removed from the atmosphere and stored in living tree biomass. As trees die

and otherwise deposit litter and debris on the forest floor, carbon is released to the atmosphere and is also transferred to the litter, dead wood, and soil pools by organisms that facilitate decomposition.

The net change in forest carbon is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of all harvested biomass carbon to the atmosphere. Instead, harvesting transfers a portion of the carbon stored in wood to a "product pool." Once in a product pool, the carbon is emitted over time as CO_2 in the case of decomposition and as CO_2, CH_4, N_2O, CO, and NO_x when the wood product combusts. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases carbon immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest carbon stocks) and subsequent combustion are implicitly estimated in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the portion of harvested timber combusted to produce energy does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and carbon is released to the atmosphere. If wood products are disposed of in SWDS, the carbon contained in the wood may be released many years or decades later or may be stored almost permanently in the SWDS. These latter fluxes, with the exception of CH_4 from wood in SWDS, which is included in the Waste sector, are also estimated in the LULUCF sector.

Net Change in Carbon Stocks within Forest Land of the United States

This section describes the general method for quantifying the net changes in carbon stocks in the five carbon storage pools and two harvested wood pools (a more detailed description of the methods and data is provided in Annex 3.13). The underlying methodology for determining carbon stock and stock change relies on data from the national forest inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual NFI is implemented across all U.S. forest lands within the conterminous 48 states, Alaska, Puerto Rico, and the U.S. Virgin Islands, and periodic inventories are available for Hawaii and some of the other U.S. Territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the carbon estimates (Domke et al. 2022; Westfall et al. 2023). First, in the conterminous 48 states and coastal southeast and southcentral Alaska, the total carbon stocks are estimated for each carbon storage pool at the individual NFI plot, next the annual net changes in carbon stocks for each pool at the population level are estimated, and then the changes in stocks are summed for all pools to estimate total net flux at the population level (e.g., U.S. state). Changes in carbon stocks from disturbances, such natural disturbances (e.g., wildfires, insects/disease, wind) or harvesting, are included in the net changes (see Box 6-3 for more information). For instance, an inventory conducted after a fire implicitly includes only the carbon stocks remaining on the NFI plot. The IPCC (2006) recommends estimating changes in carbon stocks from forest lands according to several land-use types and conversions, specifically forest land remaining forest land and land converted to forest land, with the former being lands that have been forest lands for 20 years or longer and the latter being lands (i.e., croplands, grassland, wetlands, settlements and other lands) that have been converted to forest lands for less than 20 years.

The methods and data used to delineate forest carbon stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of estimation approaches was used to compile estimates in this *Inventory*. Methods for compiling carbon stocks and stock changes on forest land in interior Alaska are different from those used for estimation in the conterminous U.S. and coastal Alaska due to the recency of the operational FIA inventory in that region and differences in sampling protocols (see Annex 3.13 for more details). Finally, estimates of carbon stocks and stock changes on forest land in Hawaii and the U.S. Territories of American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands (hereafter referred to as the U.S. Territories) are included for the first time in this *Inventory*. The FIA program has conducted annual inventories in parts of Puerto Rico (Mainland, Vieques, Culebra) and the U.S. Virgin Islands and periodic inventories in Hawaii, American Samoa, Guam, Northern Mariana Islands, and Puerto Rico (Mona Island). These inventories in combination with published estimates of carbon stocks, stock changes, and IPCC (2019) default estimates were used to compile estimates of carbon stocks and stock changes on forest land for these regions (see Annex 3.13 for more details).

Forest Area in the United States

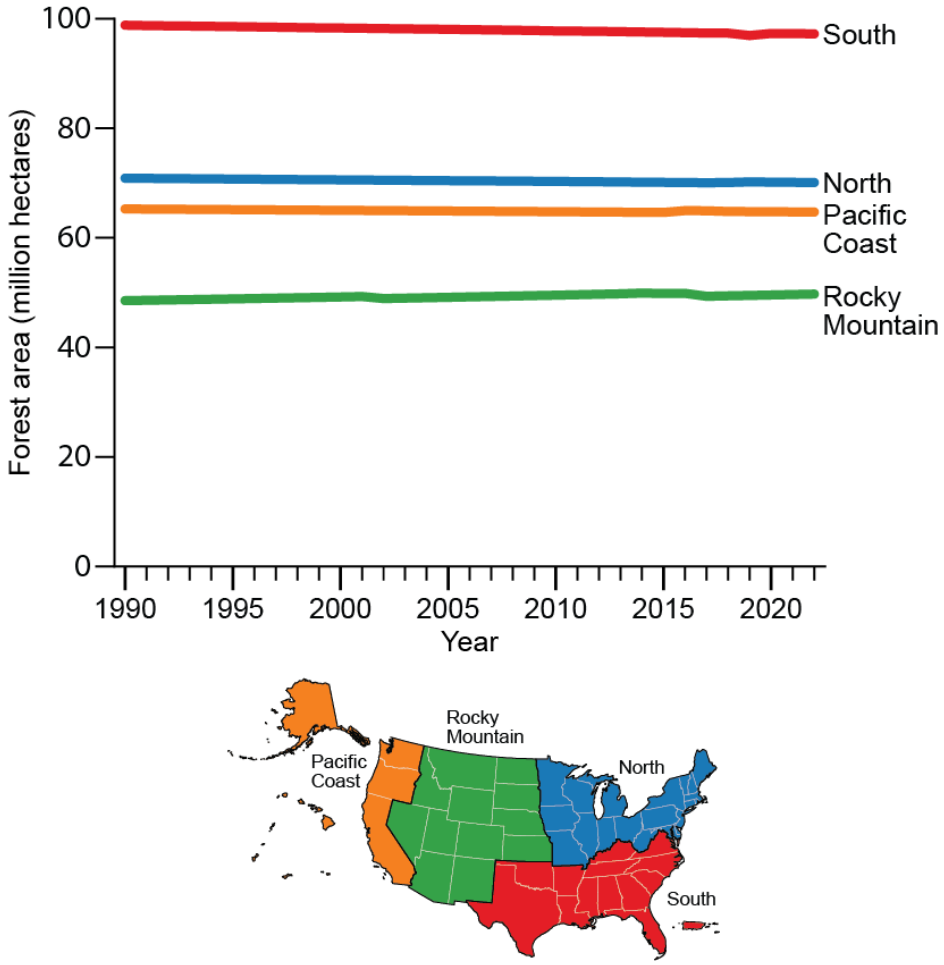
Approximately 32 percent of the managed U.S. land area is estimated to be forested based on the U.S. definition of forest land as provided in Section 6.1. All annual and periodic NFI plots included in the public FIA database as of September 2023 (which includes data collected through 2022 – note that the COVID 19 pandemic resulted in delays in data collection in many states) were used in this *Inventory*. The NFIs from the conterminous United States (USDA Forest Service 2023a, 2023b), Alaska, Hawaii, and the U.S. Territories comprise an estimated 282 million hectares of forest land that are considered managed and are included in the current *Inventory*. Some differences also exist in forest land area estimates from the latest update to the Resources Planning Act (RPA) Assessment (Oswalt et al. 2019) and the forest land area estimates included in this report, which are based on the annual and periodic NFI data through 2022 for all states (USDA Forest Service 2023b; Nelson et al. 2020). The methods for compiling area estimates for Hawaii and the U.S. Territories in this section are different from those in Section 6.1 because they do not rely on FIA data. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation (see Annex 3.13). This prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. Agroforestry systems that meet the definition of forest land are also not currently included in the current *Inventory* since they are not explicitly inventoried (i.e., classified as an agroforestry system) by either the FIA program or the Natural Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 67 percent (208 million hectares) of U.S. forests in Alaska, Hawaii and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Approximately ten percent of Alaska forest land and 73 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland in the conterminous United States, Alaska, and Hawaii, nearly 33 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 102 million hectares are lower productivity forest lands (Oswalt et al. 2019). Historically, the timberlands in the conterminous United States have been more frequently or intensively surveyed than the forest lands removed from production because they do not meet the minimum level of productivity.

Since the late 1980s, gross forest land area in Alaska, Hawaii, and the conterminous United States has increased by about 13 million hectares (Oswalt et al. 2019). The southern region of the United States contains the most forest land (Figure 6-4). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Estimated forest land area in the conterminous United States and Alaska represented in this *Inventory* is stable, but there are substantial conversions as described in 6.1 and each of the land conversion sections for each land-use category (e.g., land converted to cropland, land converted to grassland). The major influences on the net carbon flux from forest land across the 1990 to 2022 time series are management activities, natural disturbance, particularly wildfire, and the ongoing impacts of current and previous land-use conversions. These activities affect the net flux of carbon by altering the amount of carbon stored in forest ecosystems and also the area converted to forest land. For example, intensified management of forests that leads to an increased rate of growth of aboveground biomass (and possible changes to the other carbon storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of carbon in the aboveground biomass pool.[29] Though harvesting forests removes much of the carbon in aboveground biomass (and possibly changes carbon density in other pools), on average, the estimated volume of annual net growth in aboveground tree biomass in the conterminous United States is essentially twice the volume of annual removals on timberlands (Oswalt et al. 2019). The net effects of forest management and changes in forest land remaining forest land are captured in the estimates of carbon stocks and fluxes presented in this section.

[29] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Species-specific carbon fractions are used to convert dry biomass to carbon (Westfall et al. 2023).

Figure 6-4: Changes in Forest Area by Region for Forest Land Remaining Forest Land in the conterminous United States and Alaska (1990-2022)



Forest Carbon Stocks and Stock Change

In the forest land remaining forest land category, forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting have resulted in net removal (i.e., net sequestration or accumulation) of carbon each year from 1990 through 2022. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century, many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence carbon fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests and natural disturbance have also affected net carbon fluxes. Because most of the timber harvested from U.S. forest land is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, substantial quantities of carbon in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). By maintaining current harvesting practices and regeneration activities on forest lands, along with continued input of harvested wood into the HWP pool, carbon stocks in the forest land remaining forest land category are likely to continue to increase in the near term, though

possibly at a slower rate. Changes in carbon stocks in the forest ecosystem and harvested wood pools associated with forest land remaining forest land were estimated to result in net removal of 787.0 MMT CO_2 Eq. (214.6 MMT carbon) in 2022 (Table 6-8, Table 6-9, Table A-203, Table A-204 and state-level estimates in Table A-207). The estimated net uptake of carbon in the Forest Ecosystem was 694.3 MMT CO_2 Eq. (189.3 MMT carbon) in 2022 (Table 6-8 and Table 6-9). The majority of this uptake in 2022, 491.7 MMT CO_2 Eq. (134.1 MMT carbon), was from aboveground biomass. Overall, estimates of average carbon density in forest ecosystems (including all pools) increased consistently over the time series with an average of approximately 208 MT carbon ha^{-1} from 1990 to 2022. This was calculated by dividing the forest ecosystem carbon stock estimates by the forest land area estimates for every year (see Table 6-10 and Table A-206) and then calculating the mean across the entire time series, i.e., 1990 through 2022. The increasing forest ecosystem carbon density, when combined with relatively stable forest area, results in net carbon accumulation over time. However, due to an aging forest land base, increases in the frequency and severity of disturbances in forests in some regions, among other drivers of change, forest carbon density is increasing at a slower rate resulting in an overall decline in the sink strength of forest land remaining forest land in the United States. Aboveground live biomass is responsible for the majority of net carbon uptake among all forest ecosystem pools (Figure 6-5). These increases may be influenced in some regions by reductions in carbon density or forest land area due to natural disturbances (e.g., wildfire, weather, insects/disease), particularly in Alaska. The inclusion of all managed forest land in Alaska has increased the interannual variability in carbon stock change estimates over the time series, and much of this variability can be attributed to severe fire years (e.g., 2022). The distribution of carbon in forest ecosystems in Alaska is substantially different from forests in the conterminous United States. In Alaska, more than nine percent of forest ecosystem carbon is stored in the litter carbon pool whereas in the conterminous United States, less than seven percent of the total ecosystem carbon stocks are in the litter pool. Much of the litter material in forest ecosystems is combusted during fire (IPCC 2006) leading to substantial carbon losses in this pool during severe fire years (Figure 6-5, Table A-206).

The estimated net accumulation of carbon in the HWP pool, i.e., the balance of additions from the transfer of harvested wood from the forest ecosystem and losses from the current decay of wood harvested in the past, was 92.8 MMT CO_2 Eq. (25.3 MMT carbon) in 2022 (Table 6-8, Table 6-9, Table A-203, and Table A-204). The majority of this uptake, 63.9 MMT CO_2 Eq. (17.4 MMT carbon), was from solid wood and paper in SWDS. Products in use accounted for an estimated 28.8 MMT CO_2 Eq. (7.9 MMT carbon) in 2022.

Table 6-8: Net CO_2 Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Forest Ecosystem	**(851.0)**	**(770.0)**	**(779.6)**	**(726.2)**	**(765.2)**	**(749.5)**	**(694.3)**
Aboveground Biomass	(600.9)	(550.8)	(536.7)	(516.3)	(522.8)	(513.0)	(491.7)
Belowground Biomass	(116.8)	(107.5)	(105.4)	(102.3)	(102.2)	(100.9)	(96.9)
Dead Wood	(132.0)	(131.2)	(138.0)	(133.4)	(136.2)	(135.3)	(131.4)
Litter	(2.4)	20.5	(1.5)	26.5	(3.4)	(0.1)	26.4
Soil (Mineral)	2.0	(0.8)	1.3	(1.3)	(1.3)	(0.9)	(1.2)
Soil (Organic)	(1.6)	(1.0)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(106.0)**	**(93.9)**	**(86.9)**	**(96.8)**	**(94.7)**	**(92.8)**
Products in Use	(54.8)	(42.6)	(28.8)	(22.6)	(32.3)	(30.4)	(28.8)
SWDS	(69.0)	(63.4)	(65.1)	(64.3)	(64.5)	(64.3)	(63.9)
Total Net Flux	**(974.8)**	**(876.0)**	**(873.5)**	**(813.2)**	**(862.0)**	**(844.2)**	**(787.0)**

[a] These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land. See the section below on CO_2, CH_4, and N_2O emissions from drained organic soils for the methodology used to estimate the CO_2 emissions from drained organic soils. Also, Table 6-28 and Table 6-29 for non-CO_2 emissions from drainage of organic soils from both forest land remaining forest land and land converted to forest land.

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1. This results in small differences (less than 0.5 million hectares) in the forest land area estimates in this section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-206 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in interior Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Harvested wood estimates are based on results from annual surveys (see Annex 3.13, Table A-199) and models. Totals may not sum due to independent rounding.

Table 6-9: Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Forest Ecosystem	**(232.1)**	**(210.0)**	**(212.6)**	**(198.1)**	**(208.7)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(163.9)	(150.2)	(146.4)	(140.8)	(142.6)	(139.9)	(134.1)
Belowground Biomass	(31.9)	(29.3)	(28.8)	(27.9)	(27.9)	(27.5)	(26.4)
Dead Wood	(36.0)	(35.8)	(37.6)	(36.4)	(37.1)	(36.9)	(35.8)
Litter	(0.7)	5.6	(0.4)	7.2	(0.9)	(0.0)	7.2
Soil (Mineral)	0.5	(0.2)	0.4	(0.4)	(0.3)	(0.2)	(0.3)
Soil (Organic)	(0.4)	(0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(28.9)**	**(25.6)**	**(23.7)**	**(26.4)**	**(25.8)**	**(25.3)**
Products in Use	(14.9)	(11.6)	(7.8)	(6.2)	(8.8)	(8.3)	(7.9)
SWDS	(18.8)	(17.3)	(17.8)	(17.5)	(17.6)	(17.5)	(17.4)
Total Net Flux	**(265.8)**	**(238.9)**	**(238.2)**	**(221.8)**	**(235.1)**	**(230.2)**	**(214.6)**

[a] These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the carbon flux from drained organic soils. Also, see Table 6-28 and Table 6-29 for greenhouse gas emissions from non-CO_2 gases changes from drainage of organic soils from forest land remaining forest land and land converted to forest land.

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1 so there are small differences in the forest land area estimates in this Section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1). See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest ecosystem and harvested wood carbon storage pools are presented in Table 6-10. Together, the estimated aboveground biomass and soil carbon pools account for a large proportion of total forest ecosystem carbon stocks. Forest land area estimates are also provided in Table 6-10, but these do not precisely match those in Section 6.1 for forest land remaining forest land. This is because the forest land area estimates in Table 6-10 include estimates of managed forest land in Hawaii and the U.S. Territories compiled using FIA estimates in this section while the area estimates for managed forest land in Hawaii and the U.S. Territories in Section 6.1 were compiled using different methods. Differences also exist because forest land area estimates are based on the latest NFI data through 2022, and woodland areas previously included as forest land have been separated and included in the grassland categories in this *Inventory*.[30]

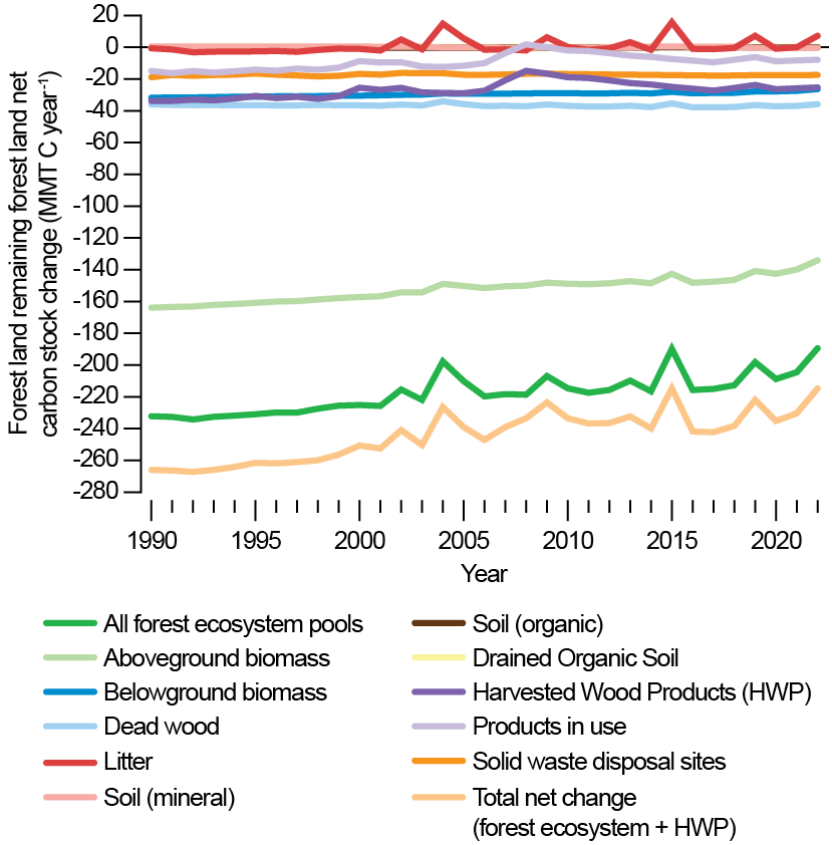
Table 6-10: Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	1990	2005	2019	2020	2021	2022	2023
Forest Area (1,000 ha)	***283,500***	***282,521***	***281,137***	***281,779***	***281,780***	***281,752***	***281,725***
Carbon Pools (MMT C)							
Forest Ecosystem	**55,142**	**58,536**	**61,519**	**61,717**	**61,926**	**62,130**	**62,320**
Aboveground Biomass	12,739	15,122	17,199	17,340	17,483	17,622	17,757
Belowground Biomass	2,255	2,718	3,124	3,151	3,179	3,207	3,233
Dead Wood	1,977	2,521	3,038	3,074	3,111	3,148	3,184
Litter	3,789	3,794	3,775	3,767	3,768	3,768	3,761
Soil (Mineral)	28,407	28,401	28,400	28,400	28,401	28,401	28,401
Soil (Organic)	5,976	5,981	5,983	5,983	5,983	5,983	5,983
Harvested Wood	**1,895**	**2,353**	**2,671**	**2,694**	**2,721**	**2,747**	**2,772**
Products in Use	1,249	1,447	1,523	1,530	1,538	1,547	1,555
SWDS	646	906	1,147	1,165	1,182	1,200	1,217
Total C Stock	**57,037**	**60,890**	**64,189**	**64,411**	**64,647**	**64,877**	**65,092**

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1 so there are small differences in the forest land area estimates in this section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base (CRT Category 4.1). See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 and Section 6.2. The forest ecosystem carbon stocks do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Harvested wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Population estimates compiled using FIA data are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2022 requires estimates of carbon stocks for 2022 and 2023.

[30] See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

Figure 6-5: Estimated Net Annual Changes in Carbon Stocks for All Carbon Pools in Forest Land Remaining Forest Land in the Conterminous United States and Alaska (1990-2022)



Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all carbon losses due to disturbances such as forest fires, because only carbon remaining in the forest is estimated. Net carbon stock change is estimated by subtracting consecutive carbon stock estimates. A forest fire disturbance removes carbon from the forest. The inventory data from the NFI on which net carbon stock estimates are based already reflect this carbon loss. Therefore, estimates of net annual changes in carbon stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states (48 states), Hawaii, Puerto Rico, and Guam as well as the portion of managed forest lands in Alaska. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO_2 estimates are based on the same methodology as applied for the non-CO_2 greenhouse gas emissions from forest fires that are also quantified in a separate section below as required by IPCC Guidance and the UNFCCC.

Emissions estimates are developed using IPCC (2019) methodology and based on U.S.-specific data and models to quantify the primary fire-specific components: area burned; availability and combustibility of fuel; fire severity (or consumption); and CO_2 and non-CO_2 emissions. Estimated CO_2 emissions for fires on forest lands in the United States for 2022 are 129.2 MMT CO_2 per year (Table 6-11). This estimate is an embedded component of the net annual forest carbon stock change estimates provided previously (i.e., Table 6-9), but this separate approach to estimating CO_2 emissions is necessary in order to associate these emissions with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that in Alaska, a portion of the forest lands are considered unmanaged, therefore the estimates for Alaska provided in Table 6-11 include only managed forest land within the state, which is consistent with carbon stock change estimates provided above.

Table 6-11: Estimates of CO_2 (MMT per Year) Emissions[a] from Forest Fires in the Conterminous 48 States, Hawaii, Puerto Rico, Guam, and Alaska

	1990	2005	2018	2019	2020	2021	2022
CO_2 emitted from fires on forest land in the Conterminous 48 States, Hawaii, Puerto Rico, and Guam (MMT yr^{-1})	11.9	28.6	77.5	19.1	124.0	156.7	71.8
CO_2 emitted from fires on managed forest land in Alaska (MM Tyr^{-1})	43.2	113.5	7.1	34	0.4	6.8	57.4
Total CO_2 emitted (MMTyr^{-1})	**55.1**	**142.2**	**84.6**	**53**	**124.4**	**163.5**	**129.2**

[a] These emissions have already been included in the estimates of net annual changes in carbon stocks, which include the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodology described herein is consistent with the *2006 IPCC Guidelines for National Inventories*. Forest ecosystem carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States and coastal southeast and southcentral Alaska, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon stocks and then subtracting between the years to obtain the stock change. The gain-loss method was used to estimate carbon stocks and net annual carbon stock changes in interior Alaska, Hawaii, and the U.S. Territories. The approaches for estimating carbon stocks and stock changes on forest land remaining forest land are described in Annex 3.13. All annual and periodic NFI plots available in the public FIA database (USDA Forest Service 2023b) were used in the current *Inventory*. Additionally, NFI plots established and measured in 2014 as part of a pilot inventory in interior Alaska were also included in this *Inventory* as were plots established and measured since 2015 as part of the operational NFI in interior Alaska. Some of the data from the pilot and operational NFI in interior Alaska are not yet available in the public FIA database. Only plots which meet the definition of forest land (see Section 6.1) are measured in the NFI; as part of the pre-field process in the FIA program, all plots or portions of plots (i.e., conditions) are classified into a land-use category. This land use information on each forest and non-forest plot was used to estimate forest land area and land converted to and from forest land over the time series. The estimates in this section of the report are based on land use information from the NFI and they may differ from the other land-use categories where area estimates reported in the Land Representation were not updated (see Section 6.1). Further, managed forest land area estimates for Hawaii and the U.S. Territories were compiled using FIA data in this section which is different from how estimates for these lands were compiled in Section 6.1 (see Annex 3.13 for details on differences).

To implement the stock-difference approach, forest land conditions in the conterminous United States and coastal Alaska were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 to t_1 was then projected to 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation. In cases where there are t_1 estimates in the last year (e.g., 2022) of the NFI no projections are necessary for those plots.

To implement the gain-loss approach in interior Alaska, forest land conditions in Alaska were observed on NFI plots from 2014 to 2022. Plot-level data from the NFI were harmonized with auxiliary data describing climate, forest structure, disturbance, and other site-specific conditions to develop non-parametric models to predict carbon stocks by forest ecosystem carbon pool as well as fluxes over the entire inventory period, 1990 to 2022. First, carbon stocks for each forest ecosystem carbon pool were predicted for the year 2016 for all NFI plot locations

(each plot representing 12,015 ha). Next, the chronosequence of sampled NFI plots and auxiliary information (e.g., climate, forest structure, disturbance, and other site-specific data) were used to predict annual gains and losses for each forest ecosystem carbon pool. The annual gains and losses were then combined with the stock estimates and disturbance information to compile plot- and population-level carbon stocks and fluxes for each year from 1990 to 2022.

To implement the gain-loss approach in Hawaii and the U.S. Territories, a combination of Tier 1 and Tier 2 methods were applied. All forest land conditions were observed on annual and periodic NFI plots from 2001 to 2019 (see Annex 3.13 for specific inventories included for each Island). Plot-level data from the NFI were harmonized with data describing ecological zone (FAO 2010), soil attributes (Johnson and Kern 2003; Deenik and McClellan, 2007, IPCC 2019), and dead wood and litter carbon stocks (Oswalt et al. 2008; IPCC 2019). Only estimates of carbon stocks in live trees were consistently available in the NFI for Hawaii and the U.S. Territories for each inventory. These estimates were used to obtain average annual carbon stock change estimates for above and belowground live trees which were applied to each forest plot to capture growth, harvest removals, and mortality. The carbon stocks and annual stock change estimates were compared with country-specific estimates (Oswalt et al. 2008; Selmants et al. 2017), and IPCC (2019) default estimates to ensure they were consistent with other sources. There were limited data available on disturbances and management activities on NFI plots over the times series so Tier 1 methods were applied for dead wood and litter. It was assumed that the average transfer rate into dead wood and litter pools is equivalent to the average transfer rate out of the dead organic matter pool so there are no net carbon stock changes included for these pools in the time series (IPCC 2006). Similarly, given data limitations on forest soils and changes on NFI plots over the time series, a Tier 1 approach was also used for soil carbon with country-specific estimates (Johnson and Kern 2003) and IPCC (2019) defaults used to estimate soil carbon stocks with no net carbon stock change reported.

To estimate carbon stock changes in harvested wood, estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the carbon in forest ecosystems within the conterminous United States and Alaska and harvested wood products for all of the United States is provided below. See Annex 3.13 for details and additional information related to the methods and data.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Forest Ecosystem Carbon from Forest Inventory

The United States applied the compilation approach described in Woodall et al. (2015a) for the current *Inventory* which removes the older periodic inventory data, which may be inconsistent with annual inventory data, from the estimation procedures. This approach enables the attribution of forest carbon accumulation by forest growth, land-use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest carbon to disturbances and delineates land converted to forest land from forest land remaining forest land. As part of this development, carbon pool science will continue and will be expanded to improve the estimates of carbon stock transfers from forest land to other land uses and include techniques to better identify land-use change (see the Planned Improvements section below).

Unfortunately, the annual FIA inventory system does not extend into the 1970s, necessitating the adoption of a system to estimate carbon stocks prior to the establishment of the annual forest inventory. The estimation of carbon stocks prior to the annual national forest inventory consisted of a modeling framework comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses carbon stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and carbon stock change or carbon stock transfer by age class. The

required inputs are estimated from more than 625,000 forest and non-forest observations recorded in the FIA national database (U.S. Forest Service 2023a, b, c). Model predictions prior to the annual inventory period are constructed from the estimation system using the annual estimates. The estimation system is driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; Westfall et al. 2022; USDA Forest Service 2023d, 2023a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five or seven-panel design, with 20 percent or 14.3 percent of the field plots typically measured each year within a state, is used in the eastern United States and a ten-panel design, with typically ten percent of the field plots measured each year within a state, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into the estimation system is to identify annual and periodic inventory datasets by state and U.S. Territory. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as "moving window" averages, which mean that a portion—but not all—of the previous year's inventory is updated each year (USDA Forest Service 2023d). Forest carbon estimates are organized according to these state surveys, and the frequency of surveys varies by state.

Using this FIA data, separate estimates were prepared for the five carbon storage pools identified by IPCC (2006) as described above. All estimates for the conterminous United States and Alaska were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2023b, 2023c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. Only live (and in some cases) standing dead wood estimates are available in the annual and periodic FIA inventories in Hawaii and the U.S. Territories. For this reason, a combination of approaches was used to obtain estimates for all carbon pools for the time series in these locations.

Carbon in Biomass

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the litter. Separate estimates were made for above- and belowground biomass components. Over the last decade, the USDA Forest Service's FIA program and collaborators from universities and industry have been developing a new national methodology for the prediction of individual-tree volume, biomass, and carbon content. The resulting methodology is referred to as the National-Scale Volume and Biomass (NSVB) framework. The previous methodology used was the Component Ratio Method (CRM) framework (Woodall et al. 2010). While CRM was nationally consistent, tree biomass was still based on the volume predicted by regional models and tree carbon was assumed to be 50-percent of biomass, regardless of species. Hence, the need for NSVB, a nationally consistent methodology for compatible predictions of tree volume, biomass, and carbon content (Westfall et al. In press).

The NSVB covers timber tree species in the conterminous United States and coastal Alaska. All other trees (i.e., trees that are woodland species and trees within Pacific and Caribbean Islands) use regional models for volume and biomass, with updated carbon fractions (when available). While NSVB did not directly update models for trees that are considered woodland species or trees within the Pacific (USDA Forest Service 2022a, b) and Caribbean Islands (collectively referred to hereafter as "non-NSVB trees"), volume, biomass, and carbon estimates for these trees have also changed. For non-NSVB trees, the standardization of tree defects and how variables are reported (i.e., whether models for total-stem or merchantable-bole volumes are available) may be reflected as differences in volume estimates. Additionally, biomass estimates for non-NSVB trees are based on regional biomass models and no longer are adjusted as they were under the CRM. Finally, updates to carbon fractions (when available) and calculation of aboveground biomass are reflected in aboveground and belowground biomass carbon estimates (see Recalculations section and Annex 3.13 for more details).

Understory vegetation is a minor component of biomass, which is defined in the FIA program as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that ten percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were based on information in Birdsey (1996) and tree biomass estimates from the FIADB. Understory biomass represented over one percent of carbon in biomass, but its contribution rarely exceeded two percent of the total carbon stocks or stock changes across all forest ecosystem carbon pools each year.

Carbon in Dead Organic Matter

Dead organic matter is calculated as three separate pools—standing dead trees, downed dead wood, and litter—with carbon stocks estimated from sample data or from models as described below. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic methods applied to live trees (Westfall et al. 2023) with additional modifications to account for decay and structural loss (Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016), was used to estimate litter carbon for every FIA plot used in the estimation framework. These estimates are now available in the FIADB (USDA Forest Service 2023b).

Carbon in Forest Soil

Soil carbon is the largest terrestrial carbon sink with much of that carbon in forest ecosystems. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of soil measurement data on forest land in the conterminous United States and coastal Alaska (O'Neill et al. 2005). Observations of mineral and organic soil carbon on forest land from the FIA program and the International Soil Carbon Monitoring Network were used to develop and implement a model framework that enabled the prediction of mineral and organic (i.e., undrained organic soils) soil carbon to a depth of 100 cm from empirical measurements collected on sample plots at a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil carbon stocks specific to forest land in the United States (Domke et al. 2017). These estimates are now available in the FIADB (USDA Forest Service 2023b). This approach allowed for separation of mineral and organic soils, the latter also referred to as Histosols, in the forest land remaining forest land category. Note that mineral and organic (i.e., undrained organic soils) soil carbon stock changes are reported to a depth of 100 cm for forest land remaining forest land to remain consistent with past reporting in this category, however for consistency across land-use categories, mineral (e.g., cropland, grassland, settlements) soil carbon is reported to a depth of 30 cm in Section 6.3 Land Converted to Forest Land. Estimates of carbon stock changes from organic soils shown in Table 6-8 and Table 6-9 include the emissions from drained organic forest soils, and the methods used to develop these estimates can be found in the Drained Organic Soils section below.

Harvested Wood Carbon

Estimates of the HWP contribution to forest carbon sinks and emissions (hereafter called "HWP contribution") were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating the HWP contribution. IPCC (2006) provides methods that allow for reporting of the HWP contribution using one of several different methodological approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP carbon stocks (see Annex 3.13 for more details about each approach). The United States uses the production approach to report HWP

contribution. Under the production approach, carbon in exported wood was estimated as if it remains in the United States, and carbon in imported wood was not included in the estimates. Though reported, U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were calculated by tracking the annual estimated additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in SWDS. The carbon loss from harvest is reported in the forest ecosystem component of the forest land remaining forest land and land converted to forest land sections and for informational purposes in the Energy sector, but the non-CO_2 emissions associated with biomass energy are included in the Energy sector emissions (see Chapter 3). EPA includes HWP within the forest chapter because forests are the source of wood that goes into the HWP estimates.

Solidwood products include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception of additions of softwood lumber to housing, which began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and USDC Bureau of the Census, among other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; AF&PA 2023; FAO 2023). Estimates for disposal of products reflects the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of carbon in wood and paper products in use in the United States,

(1B) annual change of carbon in wood and paper products in SWDS in the United States,

(2A) annual change of carbon in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of carbon in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) Carbon in imports of wood, pulp, and paper to the United States,

(4) Carbon in exports of wood, pulp and paper from the United States, and

(5) Carbon in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production estimation approach. A key assumption for estimating these variables that adds uncertainty in the estimates was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty estimation for forest ecosystem CO_2 flux using IPCC Approach 1 (Table 6-12 and Table A-214 for state-level uncertainties). A Monte Carlo stochastic simulation of the methods described above, and probabilistic sampling of carbon conversion factors, were used to determine the HWP uncertainty using IPCC Approach 2. See Annex 3.13 for additional information. The 2022 net annual change for forest carbon stocks was estimated to be between –866.5 and –708.3 MMT CO_2 Eq. around a central estimate of –787.0 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of –769.6 to –618.9 MMT CO_2 Eq. around a central estimate of –694.3 MMT CO_2 Eq. for forest ecosystems and –118.0 to -70.0 MMT

CO_2 Eq. around a central estimate of -92.8 MMT CO_2 Eq. for HWP.

Table 6-12: Quantitative Uncertainty Estimates for Net CO_2 Flux from Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem C Pools[a]	CO_2	(694.3)	(769.6)	(618.9)	-10.9%	+10.9%
Harvested Wood Products[b]	CO_2	(92.8)	(118.0)	(70.0)	-27.2%	+24.6%
Total Forest	**CO_2**	**(787.0)**	**(866.5)**	**(708.3)**	**-10.1%**	**+10.0%**

[a] Range of flux estimates predicted through a combination of sample-based and model-based uncertainty for a 95 percent confidence interval, IPCC Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, IPCC Approach 2.

Notes: Parentheses indicate negative values or net uptake. Totals may not sum due to independent rounding.

QA/QC and Verification

The FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous U.S., dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for carbon stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available (USDA Forest Service 2023d).

General quality control procedures were used in performing calculations to estimate carbon stocks based on survey data. For example, the carbon datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Oswalt et al. (2019) or selected population estimates generated from the FIA database, which are available at an FIA internet site (USDA Forest Service 2023b). Agreement between the carbon datasets and the original inventories is important to verify accuracy of the data used.

Additional verification analyses are currently underway to compare forest carbon stock change estimates developed using the NSVB model to estimates stemming from other forest biomass models as well as remote sensing imagery.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from USDC Bureau of the Census and USDA Forest Service surveys of production and trade, among other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; AF&PA 2023; FAO 2023). Factors to convert wood and paper to units of carbon are based on estimates by industry and U.S. Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual carbon change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of carbon in houses standing in 2001 needs to match an independent estimate of carbon in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards used in the Waste sector each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in carbon in products in use in the United States and, to a lesser degree,

reduce uncertainty in estimates of annual change in carbon in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

There were several methodological improvements implemented in the current *Inventory* which have resulted in substantial changes when compared to the previous (1990 through 2021) *Inventory*.

First, there were new FIA data included for several states, in some cases, multiple years of new data in this *Inventory* resulting from delays that occurred due to the global pandemic. Delays still exist in some states so it is possible that multiple years of data may be available in the years ahead leading to small changes in forest ecosystem carbon stocks and stock changes throughout the time series. These changes are most notable in the conterminous United States (Table 6-14) and coastal southeast and southcentral Alaska (Table 6-15). In coastal Alaska, remeasurement data from the FIA program facilitated the use of the compilation system used in most of the conterminous United States, improving consistency and facilitating the disaggregation of forest land conversions in this region for the first time. This transition in compilation methodology resulted in a 10.6 percent increase in forest land area (449,287 ha) in coastal Alaska which contributed, in part, to increases in forest ecosystem carbon stocks across all pools (Table 6-15).

This *Inventory* also implemented new methods for estimating standing live and dead aboveground biomass carbon in the FIA program (Westfall et al. 2023). These new methods, leveraging the newly developed national-scale volume and biomass framework (NSVB), represent nearly a decade of research and development in the FIA program. The new methods: 1) greatly simplify predictions of aboveground biomass because only five model specifications are used nationally instead of dozens of species- and species-group specific models used in each region and/or state, 2) eliminate administrative boundaries (e.g., regions or states) in favor of ecologically-based regions (i.e., ecodivisons) to capture variation in tree size and volume (or biomass) within species or species groups, 3) models are based on tree measurements from in-situ data which also facilitates more accurate quantification of model uncertainty, 4) result in consistent model behavior for all tree species and sizes, and 5) use species-specific carbon fractions for biomass to carbon conversions compared to the previous method which assumed a default 50 percent biomass to carbon fraction.

The implementation of the NSVB models resulted in an increase in estimates of aboveground biomass carbon stocks on forest land in the United States of approximately 11 percent (1,761.9 MMT C) in the current *Inventory* for the year 2022 relative to the previous *Inventory* estimate for the year 2022 (Table 6-13) and accounted for 34 percent of the total increase in estimates of forest carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year (Table 6-13). These increases can largely be attributed to more accurate characterization of top and limb biomass in the new models (Westfall et al. 2023). This also led to small increases in estimates of belowground biomass carbon stocks since that model is based on a ratio of aboveground biomass. There were also increases of more than 11 percent (321 MMT C) in estimates of dead wood carbon stocks due to the implementation of the new NSVB models in the FIA program for standing dead trees (Table 6-13), which accounted for 6.2 percent of the increases in estimates of forest ecosystem carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year.

The litter and soil model framework used in this *Inventory* and implemented across the entire time series was formally adopted in the FIA program this year and predictions compiled using this framework are now available in the public FIA database (USDA Forest Service 2023b). As part of the formal adoption of these methods in the FIA program, all variables and associated datasets used in the models were evaluated. New climate normals for the time period 1991 to 2020 were included in both the litter and soil models using PRISM data for the conterminous United States and climate normals for 1981 to 2010 (the only period available) were included for the first time in coastal Alaska. Collectively, these updates and improvements resulted in carbon stock estimates that were 10.1 percent larger (3,150.7 MMT C) in this *Inventory* relative to the previous *Inventory* for mineral and organic soil in the United States and overall accounted for approximately 48 percent of the total increases in forest carbon stock

in the current *Inventory* for the year 2022 when compared to the previous *Inventory* for the same year (Table 6-13, Table 6-14). In coastal Alaska, there were comparable increases in predictions in the *Inventory* relative to previous *Inventories*. These increases can be attributed to increases in estimates of forest land area in coastal Alaska as well as the incorporation of climate data in the litter and soil models. Estimates of litter carbon stocks also decreased slightly on forest land remaining forest land relative to the previous Inventory (Table 6-13) due to the implementation of the NSVB models where the litter model relies on estimates of aboveground biomass as a model parameter. Finally, new data on wildfire in Interior Alaska in the latest *Inventory* also contributed to updated estimates in the time series for this area of forest land where there were decreases in the estimates of all but the organic soil carbon pools (Table 6-16). Collectively these updates and improvements resulted in a 2.3 percent decrease (119.1 MMT C) in estimates of litter carbon stocks on forest land in the United States

Managed forest land in Hawaii and several U.S. Territories[31] were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory*. While the inclusion of these forest land areas represents a relatively small increase in forest area and forest ecosystem carbon stocks overall, their inclusion represents an important improvement toward completeness in this *Inventory*.

Table 6-13: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***279,800***	***281,752***	***281,725***
Carbon Pools (MMT C)			
Forest	**56,951**	**62,130**	**62,320**
Aboveground Biomass	15,861	17,622	17,757
Belowground Biomass	3,143	3,207	3,233
Dead Wood	2,827	3,148	3,184
Litter	3,888	3,768	3,761
Soil (Mineral)	25,916	28,401	28,401
Soil (Organic)	5,317	5,983	5,983
Harvested Wood	**2,749**	**2,747**	**2,772**
Products in Use	1,549	1,547	1,555
SWDS	1,200	1,200	1,217
Total Stock	**59,701**	**64,877**	**65,092**

Note: Totals may not sum due to independent rounding.

Table 6-14: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***249,821***	***250,036***	***249,999***
Carbon Pools (MMT C)			
Forest	**46,575**	**51,195**	**51,391**
Aboveground Biomass	14,947	16,641	16,773
Belowground Biomass	2,959	3,006	3,032
Dead Wood	2,558	2,883	2,920
Litter	2,474	2,383	2,384
Soil (Mineral)	23,086	25,467	25,467
Soil (Organic)	550	815	815

[31] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

Note: Totals may not sum due to independent rounding.

Table 6-15: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Coastal Southeast and Southcentral Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***4,222***	***4,671***	***4,681***
Carbon Pools (MMT C)			
Forest	**1,235**	**1,458**	**1,460**
Aboveground Biomass	362	421	423
Belowground Biomass	76	85	85
Dead Wood	94	107	107
Litter	129	130	130
Soil (Mineral)	411	470	470
Soil (Organic)	163	245	245

Note: Totals may not sum due to independent rounding.

Table 6-16: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***25,758***	***25,758***	***25,758***
Carbon Pools (MMT C)			
Forest	**9,142**	**9,192**	**9,183**
Aboveground Biomass	551	485	484
Belowground Biomass	107	92	92
Dead Wood	176	154	153
Litter	1,285	1,248	1,240
Soil (Mineral)	2,419	2,308	2,308
Soil (Organic)	4,604	4,905	4,905

Note: Totals may not sum due to independent rounding.

Table 6-17: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***NE***	***1,287***	***1,287***
Carbon Pools (MMT C)			
Forest	**NE**	**285**	**286**
Aboveground Biomass	NE	76	77
Belowground Biomass	NE	23	24
Dead Wood	NE	4	4
Litter	NE	7	7
Soil (Mineral)	NE	156	156
Soil (Organic)	NE	19	19

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

The new FIA data and methodological improvements described throughout this text and specifically in this section on recalculations of estimates of forest ecosystem carbon stocks extend to forest ecosystem carbon stock changes in the current *Inventory*. In total, estimates for the forest land remaining forest land sink increased 21.4 percent (sink estimates increased by 40.8 MMT C). On average across the time-series, these recalculations resulted in a

21.7 percent increase in estimates of the forest sink across the time series (sink estimates increased on average, 43.4 MMT C over the time series) relative to the previous *Inventory* (Table 6-18).

Changes in estimates of forest ecosystem carbon stock changes accounted for most of the increases between this *Inventory* and the previous *Inventory* (Table 6-18) and of those, new data and improvements in methods in the conterminous United States accounted for 97 percent (-41.8 MMT C) increases in estimates of forest ecosystem carbon stock changes in the current Inventory relative to the same year in the previous Inventory (Table 6-19). Estimates of carbon stock changes in the aboveground biomass pool increased by 25.2 percent in the current Inventory relative to the same year in the previous Inventory and accounted for 65.2 percent (-27.2 MMT C) of the increase in estimates from this *Inventory* (Table 6-19). These changes can be directly attributed to the implementation of the NSVB models in the FIA program. These increases extend to the belowground biomass pool where the increases in estimates of aboveground biomass resulted in increases in the estimates of belowground biomass by 23.8 percent (-5.1 MMT C). These increases accounted for 12.2 percent of the total increase in carbon stock changes in the forest ecosystem pools in this *Inventory*. There were also substantial increases in dead wood carbon stock changes which can also be attributed to the implementation of the NSVB models for standing dead trees (Westfall et al. In press). There was a 34.4 percent increase (-9.5 MMT C) in estimates of dead wood carbon stock changes between this Inventory and the same year in the previous Inventory. This increase in the estimates of dead wood accounts for 22.8 percent of the total increases in estimates of forest ecosystem carbon stock changes in this Inventory relative to the same year in the previous *Inventory* (Table 6-19).

There were also small differences in the estimates of carbon stock changes for the litter and the soil carbon pools in the conterminous United States, coastal and Interior Alaska (Table 6-19, Table 6-20, Table 6-21). These changes were all relatively small when compared to changes in live and standing dead biomass.

The inclusion of forest land in Hawaii and several U.S. Territories[32] also contributed to increases in the estimates of carbon stock changes in the current Inventory. Collectively, these areas contributed -1.3 MMT C to the forest land remaining forest land carbon sink in the year 2022 in the current *Inventory* (Table 6-22).

Finally, new data included in the HWP time series resulted in a minor decrease (< 1 percent) in carbon stocks in the HWP pools (Table 6-13) and an associated decrease of 7.9 percent (2.2 MMT C) in estimates of carbon stock changes (Table 6-18). These decreases are the result of decreases in estimates of carbon stock changes for products in use (19.4 percent) in the current *Inventory* relative to the same year in the previous *Inventory* (Table 6-18). With the easing of the global pandemic and the return of consumers to the marketplace, there was a rebound in the purchase and accumulation of solid wood products. Alternatively, paper products in use have been declining in recent years, which could be the result of greater digitization across society. These trends are expected to continue in 2023.

Table 6-18: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(161.6)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(111.6)	(139.9)	(134.1)
Belowground Biomass	(22.1)	(27.5)	(26.4)
Dead Wood	(27.6)	(36.9)	(35.8)
Litter	0.5	(0.0)	7.2
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.0)	(0.0)
Drained organic soil	0.2	0.2	0.2
Harvested Wood	**(28.0)**	**(25.8)**	**(25.3)**
Products in Use	(10.3)	(8.3)	(7.9)

[32] American Samoa, Guam, Norther Mariana Islands, U.S. Virgin Islands, and Puerto Rico

SWDS	(17.7)	(17.5)	(17.4)
Total Net Flux	**(189.6)**	**(230.2)**	**(214.6)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-19: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(158.5)**	**(200.3)**	**(195.9)**
Aboveground Biomass	(108.1)	(135.3)	(132.1)
Belowground Biomass	(21.3)	(26.4)	(25.8)
Dead Wood	(27.7)	(37.2)	(36.8)
Litter	(0.5)	(1.0)	(0.8)
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.1)	(0.1)

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-20: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Coastal Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(2.0)**	**(1.9)**	**(1.9)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)
Belowground Biomass	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.1)	(0.1)
Litter	0.0	(0.1)	(0.1)
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-21: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(1.2)**	**(1.1)**	**9.6**
Aboveground Biomass	(2.1)	(2.1)	0.4
Belowground Biomass	(0.5)	(0.5)	0.0
Dead Wood	0.4	0.4	1.1
Litter	1.0	1.0	8.0
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-22: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**NE**	**(1.4)**	**(1.3)**
Aboveground Biomass	NE	(1.0)	(1.0)
Belowground Biomass	NE	(0.3)	(0.3)
Dead Wood	NE	(0.0)	0.0

Litter	NE	0.0	(0.0)
Soil (Mineral)	NE	(0.0)	0.0
Soil (Organic)	NE	0.0	0.0

NE (Not Estimated)

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

Reliable estimates of forest carbon stocks and changes across the diverse ecosystems of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual *Inventory* submissions. Planned improvements can be broadly assigned to the following categories: development of a robust estimation and reporting system, individual carbon pool estimation, coordination with other land-use categories, and periodic and annual inventory data incorporation.

While this *Inventory* submission includes carbon change by forest land remaining forest land and land converted to forest land and carbon stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. The estimation approach used for the conterminous United States in the current *Inventory* for the forest land category operates at the state scale, whereas previously the western United States and southeast and southcentral coastal Alaska operated at a regional scale. While this is an improvement over previous Inventories and led to improved estimation and separation of land-use categories in the current *Inventory*, including coastal Alaska, research is underway to leverage all FIA data (periodic and annual inventories) and auxiliary information (i.e., remotely sensed information) to operate at finer spatial and temporal scales. As in past submissions, emissions and removals associated with natural (e.g., wildfire, insects, and disease) and human (e.g., harvesting) disturbances are implicitly included in the report given the design of the annual NFI, but not explicitly estimated. In addition to integrating auxiliary information into the estimation framework and leveraging all NFI plot measurements, alternative estimators are also being evaluated which will eliminate latency in population estimates from the NFI, improve annual estimation and characterization of interannual variability, facilitate attribution of fluxes to particular activities, and allow for streamlined harmonization of NFI data with auxiliary data products. This will also facilitate separation of prescribed and wildfire emissions in future reports. The transparency and repeatability of estimation and reporting systems will be improved through the dissemination of open-source code (e.g., R programming language) in concert with the public availability of the periodic and annual NFI (USDA Forest Service 2023b). Also, several FIA database processes are being institutionalized to increase efficiency and QA/QC in reporting and further improve transparency, completeness, consistency, accuracy, and availability of data used in reporting. Finally, a combination of approaches was used to estimate uncertainty associated with carbon stock changes in the forest land remaining forest land category in this report. There is research underway investigating more robust approaches to estimate total uncertainty (Clough et al. 2016), which will be considered in future *Inventory* reports.

The modeling framework used to estimate downed dead wood within the dead wood carbon pool (Smith et al. 2022) will be updated similar to the litter (Domke et al. 2016) and soil carbon pools (Domke et al. 2017). With the implementation of the new models for volume, biomass, and carbon estimation for live and standing dead trees, the methods for litter and soil carbon estimation used in this *Inventory* and recent *Inventories* have been adopted in the FIA program so there is now alignment and consistency between litter and soil carbon estimates in this *Inventory* and the FIA database. Finally, components of other pools, such as carbon in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014; Johnson et al. 2017), are being explored but may require additional investment in field inventories before improvements can be realized in the *Inventory* report.

The foundation of forest carbon estimation and reporting is the annual NFI. The ongoing annual surveys by the FIA program are expected to improve the accuracy and precision of forest carbon estimates as new state surveys become available (USDA Forest Service 2023b). With the exception of Wyoming (which will have sufficient remeasurements in the years ahead), all other states in the conterminous United States and coastal Alaska now

have sufficient annual NFI data to consistently estimate carbon stocks and stock changes for the future using the state-level compilation system. The FIA program continues to install permanent plots in interior Alaska as part of the operational NFI, and as more plots are added to the NFI, they will be used to improve estimates for all managed forest land in Alaska. Estimates of carbon stocks and stock changes for Hawaii and the U.S. Territories were included in this *Inventory* using Tier 1 and Tier 2 methods. The methods used to include all managed forest land in the conterminous United States will be used in future Inventories for Hawaii and U.S. Territories as additional forest carbon data become available (only a small number of plots from Hawaii are currently available from the annualized sampling design). To that end, research is underway to incorporate all NFI information (both annual and periodic data) and the dense time series of remotely sensed data in multiple inferential frameworks for estimating greenhouse gas emissions and removals as well as change (i.e., disturbance or land-use changes) detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid the efforts to improve estimates for interior Alaska, Hawaii, and the U.S. Territories, as well as the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling (i.e., more samples) of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve spatial and temporal resolution of carbon pools (Westfall et al. 2013) as this information becomes available. Increased sample intensity of some carbon pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The NFI sampling frame extends beyond the forest land-use category (e.g., woodlands, which fall into the grasslands land-use category, and urban areas, which fall into the settlements land-use category) with inventory-relevant information for trees outside of forest land. These data will be utilized as they become available in the NFI.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using U.S.-specific data and models for annual area of forest burned, fuel, consumption, and emission consistent with IPCC (2019). In 2022, emissions from this source were estimated to be 9.1 MMT CO_2 Eq. of CH_4 and 5.7 MMT CO_2 Eq. of N_2O (Table 6-23; kt units provided in Table 6-24). The estimates of non-CO_2 emissions from forest fires include the conterminous 48 states, Hawaii, Puerto Rico, Guam and managed forest land in Alaska (Ogle et al. 2018) because the fire data in use with the current methods identifies fires on these areas within the interval 1990 through 2022.

Table 6-23: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	3.4	9.2	6.0	3.4	9.8	12.7	9.1
N_2O	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Total	**5.8**	**15.4**	**9.7**	**5.7**	**15.3**	**19.9**	**14.8**

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

Note: Totals may not sum due to independent rounding.

Table 6-24: Non-CO_2 Emissions from Forest Fires (kt)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	122	328	213	120	349	452	327
N_2O	9	24	14	9	21	27	21
CO	3179	8447	4648	3054	7266	9598	7593
NO_x	49	124	93	51	123	160	121

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

Methodology and Time-Series Consistency

Non-CO_2 emissions from forest fires—primarily CH_4 and N_2O emissions—were calculated consistent with IPCC (2019) methodology, which represent updates of the IPCC (2006) guidance on reporting fire emissions. For the conterminous states and Alaska, estimates were developed with U.S.-specific data and models on area burned, fuel, consumption, and emissions as provided through the Wildland Fire Emissions Inventory System calculator (WFEIS, French et al. 2011, 2014). However, these fire emissions models did not extend to include Hawaii, Puerto Rico, or Guam, so forest fire estimates for these areas relied on Tier 1 emissions factors (IPCC 2019). Spatial definitions of wildland burned areas were the starting point for all estimates, from WFEIS or Tier 1. The three burned area datasets in use are the Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007), MODIS burned area mapping (MODIS MCD64A1 V6.1, Giglio et al. 2018), and Wildland Fire Interagency Geospatial Service (WFIGS) fire perimeters (WFIGS 2023). The MTBS data available for this report (MTBS 2023) included fires from 1990 through 2021 for all states and Puerto Rico (the exception was Alaska 2021 where emissions calculations were not available). The MODIS-based records include 2001 through 2022 for the 48 conterminous states plus Alaska. The WFIGS-based records for 2020 through 2022 included all states plus Puerto Rico and Guam. Note that N_2O emissions are not included in WFEIS calculations; the emissions provided here are based on the average N_2O to CO_2 ratio of 0.000166 (Larkin et al. 2014; IPCC 2019). See the emissions from forest fires section in Annex 3.13 for further details on all fire-related emissions calculations for forests. Consistent use of available data sources, data processing, and calculation methods were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty estimates for non-CO_2 emissions from forest fires are based on a Monte Carlo (IPCC Approach 2) approach to propagate variability among the alternate WFEIS annual estimates per state. Uncertainty in parts of the WFEIS system are not currently quantified. Among potential sources for future analysis are burned areas from MTBS, WFIGS, or MODIS, the fuels models or the Consume model (Prichard et al. 2014). See Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-25.

Table 6-25: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	9.1	6.2	12.1	-32%	+32%
Non-CO_2 Emissions from Forest Fires	N_2O	5.7	3.6	7.8	-36%	+37%

[a] These estimates include non-CO_2 emissions from forest fires on forest land remaining forest land and land converted to forest land.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for estimating non-CO_2 emissions from forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process and results were consistent with values expected from those calculations. The QA/QC procedures did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The methods used in the current (1990 through 2022) *Inventory* to compile estimates of non-CO_2 emissions from forest fires represent a slight change relative to the previous (1990 through 2021) *Inventory*. The basic components of calculating forest fire emissions (IPCC 2019) remain unchanged, but the WFEIS-based estimates now include MTBS, WFIGS, and MODIS based burns (depending on year). The MTBS and WFIGS based estimates are now calculated per burn event (i.e., separately for each forest fire), which improves precision for scaling or allocating emissions such as to managed versus unmanaged lands in Alaska.

An additional source of change leading to recalculations are recent and ongoing updates to the MTBS fire records (i.e., including both most-recent as well as possible updates to past years' fires). The WFEIS calculations now use version 6.1 of the MODIS burned area model and updated versions of the Fuel Characteristic Classification System (FCCS) fuel layer and the Consume model (see WFEIS 2023) for additional details on updates. The addition of forest fire emissions for Hawaii, Puerto Rico, and Guam had little effect on the magnitude of overall emissions.

Estimates of non-CO_2 emissions from forest fires (e.g., Table 6-24) are lower for most years over the time series 1990-2021 in comparison with the previous Inventory (EPA 2023), with an average decrease of 12 percent across all years. For, 2021 the estimate decreased from 24.4 to 19.9 MMT CO_2 Eq. (an 18.7 percent decrease). Changes over the time series are expected because the entire interval is recalculated each year in response to modifications in the fire datasets that can affect all years. For example, MTBS updates burn perimeters for all years as data resolution changes. This year, the WFEIS calculator updated a fuel dataset as well as the Consume model (noted above). The addition of estimates for Hawaii, Puerto Rico, and Guam had negligible effect on the estimates.

Planned Improvements

Continuing improvements are planned for developing better fire and site-specific estimates for forest fires, for example, improving on the Tier-1 factors currently employed for Hawaii, Puerto Rico, and Guam. Additional focus will be on addressing three aspects of reporting: best use of WFEIS, better resolution of uncertainty as discussed above, and identification of burned areas that are not currently captured by the burn records in use.

N_2O Emissions from N Additions to Forest Soils

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire area of forest land.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location through volatilization in the form of ammonia (NH_3) and nitrogen oxide (NO_x), in addition to leaching and runoff of nitrates (NO_3), and later converted into N_2O at off-site locations. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct soil N_2O emissions from forest land remaining forest land and land converted to forest land[33] in 2022 were 0.3 MMT CO_2 Eq. (1.2 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2022 were 0.4 MMT CO_2 Eq. (1.5 kt) and have increased by 455 percent from 1990 to 2022. Total forest soil N_2O emissions are summarized in Table 6-26.

[33] The N_2O emissions from land converted to forest land are included with forest land remaining forest land because it is not currently possible to separate the activity data by land use conversion category.

Table 6-26: N_2O Fluxes from Soils in Forest Land Remaining Forest Land and Land Converted to Forest Land (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2018	2019	2020	2021	2022
Direct N_2O Fluxes from Soils							
MMT CO_2 Eq.	0.1	0.3	0.3	0.3	0.3	0.3	0.3
kt N_2O	0.2	1.2	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Fluxes from Soils							
MMT CO_2 Eq.	+	0.1	0.1	0.1	0.1	0.1	0.1
kt N_2O	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Total (MMT CO_2 Eq.)	**0.1**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total (kt N_2O)	**0.3**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 kt.

Note: Totals may not sum due to independent rounding. The N_2O emissions from land converted to forest land are included with forest land remaining forest land because it is not currently possible to separate the activity data by land use conversion category.

Methodology and Time-Series Consistency

The IPCC Tier 1 approach is used to estimate N_2O from soils within forest land remaining forest land and land converted to forest land. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also incorporated N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Fertilizer application is rare for hardwoods and therefore not included in the inventory (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005 through 2022, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir stands (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2022, so data from 2004 are used for these years. The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of one percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions.

The same method is applied in all years of this *Inventory* to ensure time-series consistency from 1990 through 2022.

Uncertainty

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic carbon availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default

methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving nitrogen fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only applications of synthetic nitrogen fertilizers to forest are captured in this *Inventory*, so applications of organic nitrogen fertilizers are not estimated. However, the total quantity of organic nitrogen inputs to soils in the United States is included in the *Inventory* within the agricultural soil management source category (Section 5.4) and settlements remaining settlements (Section 6.10).

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[34] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-27. Direct N_2O fluxes from soils in 2022 are estimated to be between 0.1 and 1.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the emission estimate of 0.3 MMT CO_2 Eq. for 2022. Indirect N_2O emissions in 2022 are 0.1 MMT CO_2 Eq. and have a range are between 0.01 and 0.3 MMT CO_2 Eq., which is 86 percent below to 238 percent above the emission estimate for 2022.

Table 6-27: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in Forest Land Remaining Forest Land and Land Converted to Forest Land (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
Forest Land Remaining Forest Land			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	0.3	0.1	1.0	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.3	-86%	+238%

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The spreadsheet containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified based on the sources of these data consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

CO_2, CH_4, and N_2O Emissions from Drained Organic Soils[35]

Drained organic soils on forest land are identified separately from other forest soils largely because mineralization of the exposed or partially dried organic material results in continuous CO_2 and N_2O emissions (IPCC 2006). In addition, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*

[34] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

[35] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both Forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

(IPCC 2014) calls for estimating CH_4 emissions from these drained organic soils and the ditch networks used to drain them.

Organic soils are identified on the basis of thickness of organic horizon and percent organic matter content. All organic soils are assumed to have originally been wet, and drained organic soils are further characterized by drainage or the process of artificially lowering the soil water table, which exposes the organic material to drying and the associated emissions described in this section. The land base considered here is drained inland organic soils that are coincident with forest area as identified by the NFI of the USDA Forest Service (USDA Forest Service 2022b).

The estimated area of drained organic soils on forest land is 70,849 ha and did not change over the time series based on the data used to compile the estimates in the current *Inventory*. These estimates are based on permanent plot locations of the NFI (USDA Forest Service 2022b) coincident with mapped organic soil locations (STATSGO2 2016), which identifies forest land on organic soils. Forest sites that are drained are not explicitly identified in the data, but for this estimate, planted forest stands on sites identified as mesic or xeric (which are identified in USDA Forest Service 2022c, d) are labeled "drained organic soil" sites.

Land use, region, and climate are broad determinants of emissions as are more site-specific factors such as nutrient status, drainage level, exposure, or disturbance. Current data are limited in spatial precision and thus lack site specific details. At the same time, corresponding emissions factor data specific to U.S. forests are similarly lacking. Tier 1 estimates are provided here following IPCC (2014). Total annual non-CO_2 emissions on forest land with drained organic soils in 2022 are estimated as 0.1 MMT CO_2 Eq. per year (Table 6-28; kt units provided in Table 6-29).

The Tier 1 methodology provides methods to estimate emissions of CO_2 from three pathways: direct emissions primarily from mineralization; indirect, or off-site, emissions associated with dissolved organic carbon releasing CO_2 from drainage waters; and emissions from (peat) fires on organic soils. Data about forest fires specifically located on drained organic soils are not currently available; as a result, no corresponding estimate is provided here. Non-CO_2 emissions provided here include CH_4 and N_2O. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. Emission of N_2O can be significant from these drained organic soils in contrast to the very low emissions from wet organic soils.

Table 6-28: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.1	0.1	0. 1	0.1	0.1
Total	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] This table includes estimates from forest land remaining forest land and land converted to forest land.

[b] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

Note: Totals may not sum due to independent rounding.

Table 6-29: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (kt)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	1	1	1	1	1	1	1
N_2O	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

[a] This table includes estimates from forest land remaining forest land and land converted to forest land.

[b] Estimates of CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both forest land remaining forest land and land converted to forest land in order to allow for reporting of all carbon stock changes on forest lands in a complete and comprehensive manner.

Methodology and Time-Series Consistency

The Tier 1 methods for estimating CO_2, CH_4 and N_2O emissions from drained inland organic soils on forest lands follow IPCC (2006), with extensive updates and additional material presented in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). With the exception of quantifying area of forest on drained organic soils, which is user-supplied, all quantities necessary for Tier 1 estimates are provided in Chapter 2, Drained Inland Organic Soils of IPCC (2014).

Estimated area of drained organic soils on forest land is 70,849 ha based on analysis of the permanent NFI of the USDA Forest Service and did not change over the time series. The most recent plot data per state within the inventories were used in a spatial overlay with the STATSGO2 (2016) soils data, and forest plots coincident with the soil order histosol were selected as having organic soils. Information specific to identifying "drained organic" are not in the inventory data so an indirect approach was employed here. Specifically, artificially regenerated forest stands (inventory field STDORGCD=1) on mesic or xeric sites (inventory field 11≤PHYSCLCD≤29) are labeled "drained organic soil" sites. From this selection, forest area and sampling error for forest on drained organic sites are based on the population estimates developed within the inventory data for each state (USDA Forest Service 2022d). Eight states, all temperate forests (including pine forest in northern Florida, which largely display characteristics of temperate forests), were identified as having drained organic soils (Table 6-30).

Table 6-30: States identified as having Drained Organic Soils, Area of Forest on Drained Organic Soils, and Sampling Error

State	Forest on Drained Organic Soil (1,000 ha)	Sampling Error (68.3% as ± Percentage of Estimate)
Florida	2.4	79
Georgia	3.7	71
Michigan	18.7	34
Minnesota	30.2	19
North Carolina	1.3	99
Virginia	2.3	102
Washington	2.1	101
Wisconsin	10.1	30
Total	**70.8**	**14**

Note: Totals may not sum due to independent rounding.

The Tier 1 methodology provides methods to estimate emissions for three pathways of carbon emission as CO_2. Note that subsequent mention of equations and tables in the remainder of this section refer to Chapter 2 of IPCC (2014). The first pathway–direct CO_2 emissions–is calculated according to Equation 2.3 and Table 2.1 as the product of forest area and emission factor for temperate drained forest land. The second pathway—indirect, or off-site, emissions—is associated with dissolved organic carbon (DOC) releasing CO_2 from drainage waters according to Equation 2.4 and Table 2.2, which represent a default composite of the three pathways for this flux: (1) the flux of DOC from natural (undrained) organic soil; (2) the proportional increase in DOC flux from drained organic soils relative to undrained sites; and (3) the conversion factor for the part of DOC converted to CO_2 after export from a site. The third pathway—emissions from (peat) fires on organic soils—assumes that the drained organic soils burn in a fire, but not any wet organic soils. However, this *Inventory* currently does not include emissions for this pathway because data on the combined fire and drained organic soils information are not available at this time; this may become available in the future with additional analysis.

Non-CO_2 emissions, according to the Tier 1 method, include methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO). Emissions associated with peat fires include factors for CH_4 and CO in addition to CO_2, but fire estimates are assumed to be zero for the current *Inventory*, as discussed above. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. From this, two separate emission factors are used, one for emissions from the area of drained soils and a second for emissions from drainage ditch waterways. Calculations are conducted according to Equation 2.6 and Tables 2.3 and 2.4, which includes the default fraction of the total area of drained organic soil which is occupied by ditches. Emissions of N_2O can be significant from these drained soils in contrast to the very low emissions from wet organic soils. Calculations are conducted according to Equation 2.7 and Table 2.5, which provide the estimate as kg N per year.

Methodological calculations were applied to the entire set of estimates for 1990 through 2022. Year-specific data are not available. Estimates are based on a single year and applied as the annual estimates over the interval.

Uncertainty

Uncertainties are based on the sampling error associated with forest area of drained organic soils and the uncertainties provided in the Chapter 2 (IPCC 2014) emissions factors (Table 6-31). The estimates and resulting quantities representing uncertainty are based on the IPCC Approach 1–error propagation. However, probabilistic sampling of the distributions defined for each emission factor produced a histogram result that contained a mean and 95 percent confidence interval. The primary reason for this approach was to develop a numerical representation of uncertainty with the potential for combining with other forest components. The methods and parameters applied here are identical to previous inventories, but input values were resampled for this *Inventory*, which results in minor changes in the number of significant digits in the resulting estimates, relative to past values. The total non-CO_2 emissions in 2022 from drained organic soils on forest land remaining forest land and land converted to forest land were estimated to be between zero and 0.150 MMT CO_2 Eq. around a central estimate of 0.068 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-31: Quantitative Uncertainty Estimates for Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
CH_4	+	+	+	-69%	+82%
N_2O	0.1	+	0.1	-118%	+132%
Total	**0.1**	**+**	**0.2**	**-107%**	**+121%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimates predicted through a combination of sample-based and IPCC defaults for a 95 percent confidence interval, IPCC Approach 1.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

IPCC (2014) guidance cautions of a possibility of double counting some of these emissions. Specifically, the off-site emissions of dissolved organic carbon from drainage waters may be double counted if soil carbon stock and change is based on sampling and this carbon is captured in that sampling. Double counting in this case is unlikely since plots identified as drained were treated separately in this chapter. Additionally, some of the non-CO_2 emissions may be included in either the wetlands or sections on N_2O emissions from managed soils. These paths to double counting emissions are unlikely here because these issues are taken into consideration when developing the estimates and this chapter is the only section directly including such emissions on forest land.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports and geospatial products become available. For example, current and recent past estimates are based on drained organic soils identified in a limited number of the conterminous states; if forests on drained organic soils are identified in additional areas including Alaska, Hawaii, Puerto Rico, or Guam, they will be included in future *Inventories*.

6.3 Land Converted to Forest Land (CRT Category 4A2)

The carbon stock change estimates for land converted to forest land that are provided in this Inventory include all forest land in an inventory year that had been in another land use(s) during the previous 20 years.[36] For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Converted lands are in this category for 20 years as recommended in the *2006 IPCC Guidelines* (IPCC 2006), after which they are classified as forest land remaining forest land. Estimates of carbon stock changes from all pools (i.e., aboveground and belowground biomass, dead wood, litter and soils), as recommended by IPCC (2006), are included in the land converted to forest land category of this *Inventory*.

Area of Land Converted to Forest in the United States[37]

Land conversion to and from forests has occurred regularly throughout United States history. The 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. Recent analyses suggest that net accumulation of forest area continues in areas of the United States, in particular the northeastern United States (Woodall et al. 2015b). Specifically, the annual conversion of land from other land-use categories (i.e., cropland, grassland, wetlands, settlements, and other lands) to forest land resulted in a fairly continuous net annual accretion of forest land area from over the time series at an average rate of 1.0 million ha year-1.

Over the 20-year conversion period used in the land converted to forest land category, the conversion of grassland to forest land resulted in the largest source of carbon transfer and uptake, accounting for approximately 38

[36] The annual NFI data used to compile estimates of carbon transfer and uptake in this section are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series.

[37] The estimates reported in this section only include the 48 conterminous states in the United States. Land use conversions to forest land in Alaska are currently included in the Forest Land Remaining Forest Land section because currently there is insufficient data to separate the changes and estimates for Hawaii were not included because there is insufficient NFI data to support inclusion at this time. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-203 for annual differences between the forest area reported in Section 6.1 and Section 6.3.

percent of the uptake annually. Estimated carbon uptake has remained relatively stable over the time series across all conversion categories (see Table 6-24). The net flux of carbon from all forest pool stock changes in 2022 was -100.3 MMT CO_2 Eq. (-27.4 MMT C) (see Table 6-24 and Table 6-25).

Mineral soil carbon stocks increased slightly over the time series for land converted to forest land. The small gains are associated with cropland converted to forest land, settlements converted to forest land, and other land converted to forest land. Much of this conversion is from soils that are more intensively used under annual crop production or settlement management, or are conversions from other land, which has little to no soil carbon. In contrast, grassland converted to forest land leads to a loss of soil carbon across the time series, which negates some of the gain in soil carbon with the other land-use conversions. Managed pasture to forest land is the most common conversion. This conversion leads to a loss of soil carbon because pastures are mostly improved in the United States with fertilization and/or irrigation, which enhances carbon input to soils relative to typical forest management activities.

Table 6-32: Net CO_2 Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(17.6)**	**(17.5)**	**(17.3)**	**(17.3)**	**(17.2)**	**(17.2)**	**(17.2)**
Aboveground Biomass	(10.2)	(10.1)	(10.0)	(10.0)	(10.0)	(10.0)	(10.0)
Belowground Biomass	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Dead Wood	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)
Litter	(3.3)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)
Mineral Soil	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(36.7)**	**(36.9)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**
Aboveground Biomass	(22.5)	(22.7)	(22.8)	(22.8)	(22.8)	(22.8)	(22.8)
Belowground Biomass	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Dead Wood	(4.0)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)
Litter	(7.6)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)
Mineral Soil	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Other Land Converted to Forest Land	**(5.2)**	**(5.3)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**
Aboveground Biomass	(2.2)	(2.2)	(2.3)	(2.3)	(2.3)	(2.3)	(2.3)
Belowground Biomass	(0.3)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Dead Wood	(0.7)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Litter	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Mineral Soil	(0.7)	(0.8)	(1.0)	(0.9)	(0.9)	(0.9)	(0.9)
Settlements Converted to Forest Land	**(31.9)**	**(31.6)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**
Aboveground Biomass	(19.8)	(19.6)	(19.5)	(19.4)	(19.4)	(19.4)	(19.4)
Belowground Biomass	(3.4)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)
Dead Wood	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)
Litter	(4.9)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)
Mineral Soil	(0.0)	(0.03)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Wetlands Converted to Forest Land	**(8.8)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**
Aboveground Biomass	(4.9)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Litter	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(59.7)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**
Total Belowground Biomass Flux	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**
Total Dead Wood Flux	**(12.0)**	**(12.0)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**
Total Litter Flux	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**
Total Mineral Soil Flux	**(0.8)**	**(0.8)**	**(1.0)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**

Total Flux	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is insufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 and Section 6.3. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see 6.10 for estimates of carbon stock change from settlement trees). It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for all organic soils are included in Table 6-8 of the Forest Land Remaining Forest Land section of the *Inventory*.

Table 6-33: Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(4.8)**	**(4.8)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(2.8)	(2.8)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Belowground Biomass	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Dead Wood	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Litter	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(10.0)**	**(10.1)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(6.1)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)
Belowground Biomass	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Land Converted to Forest Land	**(1.4)**	**(1.4)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Litter	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Mineral Soil	(0.2)	(0.2)	(0.3)	(0.2)	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(8.7)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.4)	(5.4)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Litter	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Mineral Soil	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.5)**	**(2.5)**	**(2.5)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**
Total Mineral Soil Flux	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**
Total Flux	**(27.3)**	**(27.3)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is not sufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 and Section 6.3. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 for estimates of carbon stock change from settlement trees). It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for organic soils are included in Table 6-9 and Table 6-10 of the Forest Land Remaining Forest Land section of the *Inventory*.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate stock changes in all forest carbon pools for land converted to forest land. National Forest Inventory data and IPCC (2006) defaults for reference carbon stocks were used to compile separate estimates for the five carbon storage pools. Estimates for aboveground and belowground biomass, dead wood and litter were based on data collected from the extensive array of permanent, annual NFI plots and associated models (e.g., live tree belowground biomass estimates) in the United States (USDA Forest Service 2023b, 2023c). Carbon conversion factors were applied at the individual plot and then appropriately expanded to state population estimates, which are summed to provide the national estimate. To ensure consistency in the land converted to forest land category where carbon stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

The methods used for estimating carbon stocks and stock changes in the land converted to forest land are consistent with those used for forest land remaining forest land. For land-use conversion, IPCC (2006) default biomass carbon stock values were applied in the year of conversion on individual plots to estimate the C stocks removed due to land-use conversion from croplands and grasslands. There is no biomass loss data or IPCC (2006) defaults to include transfers, losses, or gains of carbon in the year of the conversion for other land use (i.e., other lands, settlements, wetlands) conversions to forest land so these were incorporated for these conversion categories. All annual NFI plots included in the public FIA database as of September 2023 were used in this Inventory. Forest land conditions were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, aboveground tree carbon was based on Westfall et al. (2023). The component ratio method (CRM) which is a function of volume, species, and diameter was used to compile estimates for woodland species where diameter measurements are taken at root collar and to compile belowground biomass carbon for all tree species (Woodall et al. (2011a). An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each woodland tree following the same CRM method.

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For the current *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were

based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of carbon in biomass, but its contribution rarely exceeded 2 percent of the total.

Biomass losses associated with conversion from grassland and cropland to forest land were assumed to occur in the year of conversion. To account for these losses, IPCC (2006) defaults for aboveground and belowground biomass on grasslands and aboveground biomass on croplands were subtracted from sequestration in the year of the conversion. As previously discussed, for all other land use (i.e., other lands, settlements, wetlands) conversions to forest land no biomass loss data were available, and no IPCC (2006) defaults currently exist to include transfers, losses, or gains of carbon in the year of the conversion, so none were incorporated for these conversion categories. As defaults or country-specific data become available for these conversion categories, they will be incorporated.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with carbon stocks estimated from sample data or from models. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic method applied to live trees (Westfall et al. 2023, Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016) was used to estimate litter carbon for every FIA plot used in the estimation framework. Dead organic matter carbon stock estimates are included for all land-use conversions to forest land.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate mineral soil C stock changes for land converted to forest land (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003, 2006). Land use and land-use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA) and the 2017 National Resources Inventory (NRI) (USDA-NRCS 2020). The areas have been modified in the NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land-use categories (see Section 6.1 for more information). Note that soil C in this Inventory is reported to a depth of 100 cm in the forest land remaining forest land category (Domke et al. 2017) while other land-use categories report soil C to a depth of 30 cm. However, to ensure consistency in the land converted to forest land category where C stock transfers occur between land-use categories, soil C estimates were based on a 30 cm depth using methods from Ogle et al. (2003, 2006) and IPCC (2006). See Annex 3.12 for more information about this method.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Mineral soil organic C stock changes from 2021 to 2022 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. The extrapolation is based on a linear regression model with moving-average

(ARMA) errors using the 1990 to 2020 emissions data and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for land converted to forest land through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 Eq. flux (IPCC Approach 1). Uncertainty estimates for forest pool carbon stock changes were developed using the same methodologies as described in the forest land remaining forest land section for aboveground and belowground biomass, dead wood, and litter. The exception was when IPCC default estimates were used for reference carbon stocks in certain conversion categories (i.e., cropland converted to forest land and grassland converted to forest land). In those cases, the uncertainties associated with the IPCC (2006) defaults were included in the uncertainty calculations. IPCC Approach 2 was used to propagate errors with estimation of mineral soils carbon stock changes for land-use conversions, and is described in the cropland remaining cropland section.

Uncertainty estimates are presented in Table 6-34 for each land conversion category and carbon pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil carbon pools (IPCC Approach 1) and a Monte Carlo approach (IPCC Approach 2) was used for mineral soil. Uncertainty estimates were combined using the error propagation model (IPCC Approach 1). The combined uncertainty for all carbon stocks in land converted to forest land ranged from 11 percent below to 11 percent above the 2022 carbon stock change estimate of –100.3 MMT CO_2 Eq.

Table 6-34: Quantitative Uncertainty Estimates for Forest Carbon Pool Stock Changes (MMT CO_2 Eq. per Year) in 2022 from Land Converted to Forest Land by Land Use Change

Land Use/Carbon Pool	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Range[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land	(17.2)	(25.8)	(8.7)	-50%	50%
Aboveground Biomass	(10.0)	(18.4)	(1.7)	-83%	83%
Belowground Biomass	(1.7)	(2.7)	(0.7)	-61%	61%
Dead Wood	(2.2)	(3.4)	(1.0)	-56%	56%
Litter	(3.2)	(4.3)	(2.1)	-34%	34%
Non-federal Mineral Soils	(0.1)	(0.3)	0.0	-142%	142%
Federal Mineral Soils	(0.0)	(0.1)	0.1	-8,796%	8,796%
Grassland Converted to Forest Land	(37.2)	(39.6)	(34.8)	-6%	6%
Aboveground Biomass	(22.8)	(24.2)	(21.5)	-6%	6%
Belowground Biomass	(2.7)	(3.0)	(2.5)	-10%	10%
Dead Wood	(4.1)	(4.3)	(4.0)	-3%	3%
Litter	(7.7)	(8.3)	(7.2)	-7%	7%
Non-federal Mineral Soils	0.2	(0.1)	0.5	-142%	142%
Federal Mineral Soils	0.0	(0.1)	0.1	-1,310%	1,310%
Other Lands Converted to Forest Land	(5.5)	(7.8)	(3.2)	-42%	42%
Aboveground Biomass	(2.3)	(4.4)	(0.2)	-92%	92%
Belowground Biomass	(0.4)	(0.8)	0.1	-121%	121%
Dead Wood	(0.8)	(1.3)	(0.2)	-74%	74%
Litter	(1.2)	(1.8)	(0.6)	-53%	53%
Non-federal Mineral Soils	(0.9)	(1.4)	(0.5)	-49%	49%
Federal Mineral Soils	(0.0)	(0.2)	0.1	-666%	666%
Settlements Converted to Forest Land	(31.4)	(37.9)	(24.9)	-21%	21%
Aboveground Biomass	(19.4)	(25.6)	(13.3)	-32%	32%
Belowground Biomass	(3.3)	(4.6)	(2.0)	-40%	40%

Dead Wood	(3.8)	(4.9)	(2.6)	-31%	31%
Litter	(4.8)	(5.7)	(3.9)	-19%	19%
Non-federal Mineral Soils	(0.1)	(0.1)	(0.0)	-32%	32%
Federal Mineral Soils	(0.0)	(0.0)	0.0	-193%	193%
Wetlands Converted to Forest Land	(8.9)	(9.1)	(8.8)	-2%	2%
Aboveground Biomass	(5.0)	(5.2)	(4.9)	-3%	3%
Belowground Biomass	(0.9)	(0.9)	(0.9)	-3%	3%
Dead Wood	(1.2)	(1.3)	(1.2)	-4%	4%
Litter	(1.8)	(1.9)	(1.7)	-3%	3%
Non-federal Mineral Soils	0.0	0.0	0.0	0%	0%
Federal Mineral Soils	0.0	0.0	0.0	0%	0%
Total: Aboveground Biomass	(59.6)	(70.3)	(48.9)	-18%	18%
Total: Belowground Biomass	(9.0)	(10.7)	(7.2)	-19%	19%
Total: Dead Wood	(12.1)	(13.8)	(10.3)	-15%	15%
Total: Litter	(18.8)	(20.4)	(17.2)	-9%	8%
Total: Mineral Soils	(0.9)	(1.3)	(0.5)	-42%	42%
Total: Lands Converted to Forest Lands	**(100.3)**	**(111.4)**	**(89.2)**	**-11%**	**11%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NA (Not Applicable)

[a] Range of flux estimate for 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. It is not possible to separate emissions from drained organic soils between forest land remaining forest land and land converted to forest land so estimates for organic soils are included in Table 6-8 and Table 6-9 of the Forest Land Remaining Forest Land section of the *Inventory*.

QA/QC and Verification

See QA/QC and Verification sections under Forest Land Remaining Forest Land and for mineral soil estimates, Cropland Remaining Cropland.

Recalculations Discussion

The approach for estimating carbon stock changes in land converted to forest land is consistent with the methods used for forest land remaining forest Land and is described in Annex 3.13. The land converted to forest land estimates in this Inventory are based on the land-use change information in the annual NFI. All conversions are based on empirical estimates compiled using plot remeasurements from the NFI, IPCC (2006) default biomass carbon stocks removed from croplands and grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil carbon stock changes (Ogle et al. 2003, 2006; IPCC 2006). All annual NFI plots included in the public FIA database as of September 2023 were used in this *Inventory*. This is the fourth year that remeasurement data from the annual NFI were available throughout the conterminous United States (with the exception of Wyoming) and coastal southeast and southcentral Alaska to estimate land-use conversion. The availability of remeasurement data from the annual NFI allowed for consistent plot-level estimation of carbon stocks and stock changes for forest land remaining forest land and the land converted to forest land categories. Estimates in the previous *Inventory* were based on state-level carbon density estimates and a combination of NRI data and NFI data in the eastern United States. The refined analysis in this *Inventory* resulted in changes in the land converted to forest land categories. Overall, the land converted to forest land carbon stock changes increased by approximately 2 percent in 2022 between the previous *Inventory* (1990 through 2021) and the current *Inventory* (Table 6-35). While the overall change is relatively small, changes by conversion categories were substantial between this *Inventory* and the previous *Inventory*. These changes can be attributed to six methodological improvements implemented this year. First, managed pastureland was previously classified as cropland and is now classified as grassland to align with NRI definitions and classifications. This resulted in a substantial structural decrease in the cropland converted to forest land category area and associated carbon stock changes and a substantial structural increase in the grassland converted to forest land area and associated carbon stock changes.

Second, in this *Inventory* all NFI plots with evidence of water are classified as wetlands to align with definitions and classifications in the NRI. In the previous *Inventory*, some NFI plots with evidence of water were classified as other land. This methodological improvement resulted in increases in the wetlands converted to forest land category and decreases in the other land converted to forest land category. Third, estimates of carbon stocks and stock changes on managed forest land in coastal Alaska are now compiled in the same ways as the conterminous United States allowing for estimates of land conversions. This led to small increases in the area and associated carbon stock change estimates in the land converted to forest land category. Fourth, the implementation of new methods for estimating aboveground biomass carbon in live and standing dead trees resulted in changes across all land use conversion categories in the aboveground and belowground biomass, dead wood, and litter pools. Fifth, new climate normals (1990 through 2020) were incorporated in the litter model resulting in additional changes in that pool. Finally, there were new NFI data incorporated into the latest *Inventory* which contributed to changes when compared with the previous *Inventory*.

Table 6-35: Recalculations of the Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Conversion category and Carbon pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Cropland Converted to Forest Land	**(10.3)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(6.0)	(2.7)	(2.7)
Belowground Biomass	(1.2)	(0.5)	(0.5)
Dead Wood	(1.3)	(0.6)	(0.6)
Litter	(1.8)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(3.4)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(1.7)	(6.2)	(6.2)
Belowground Biomass	(0.3)	(0.7)	(0.7)
Dead Wood	(0.3)	(1.1)	(1.1)
Litter	(1.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1
Other Land Converted to Forest Land	**(2.9)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(1.3)	(0.6)	(0.6)
Belowground Biomass	(0.2)	(0.1)	(0.1)
Dead Wood	(0.4)	(0.2)	(0.2)
Litter	(0.7)	(0.3)	(0.3)
Mineral Soil	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.3)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.7)	(5.3)	(5.3)
Belowground Biomass	(1.1)	(0.9)	(0.9)
Dead Wood	(1.1)	(1.0)	(1.0)
Litter	(1.5)	(1.3)	(1.3)
Mineral soil	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(0.9)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(0.4)	(1.4)	(1.4)
Belowground Biomass	(0.1)	(0.2)	(0.2)
Dead Wood	(0.1)	(0.3)	(0.3)
Litter	(0.4)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.0)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.8)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.2)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.5)**	**(5.1)**	**(5.1)**
Total SOC (Mineral) Flux	**(0.3)**	**(0.3)**	**(0.2)**
Total Flux	**(26.8)**	**(27.4)**	**(27.4)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

There are many improvements necessary to improve the estimation of carbon stock changes associated with land-use conversion to forest land over the entire time series. First, soil carbon has historically been reported to a depth of 100 cm in the forest land remaining forest land category (Domke et al. 2017) while other land-use categories (e.g., grasslands and croplands) report soil carbon to a depth of 30 cm. To ensure greater consistency in the land converted to forest land category where carbon stock transfers occur between land-use categories, all mineral soil estimates in the land converted to forest land category in this Inventory are based on methods from Ogle et al. (2003, 2006) and IPCC (2006). Methods have recently been developed (Domke et al. 2017) to estimate soil carbon to depths of 20, 30, and 100 cm in the forest land category using in situ measurements from the FIA program within the USDA Forest Service and the International Soil Carbon Network. In subsequent Inventories, a common reporting depth will be defined for all land-use conversion categories and Domke et al. (2017) will be used in the forest land remaining forest land and land converted to forest land categories to ensure consistent reporting across all forest land. Second, due to the 5 to 10-year remeasurement periods within the FIA program and limited land-use change information available over the entire time series, estimates presented in this section may not reflect the entire 20-year conversion history. Third, since the sum of all land converted to forest land is used to adjust specific land-use conversions into forest land for the state-level estimates in the NRI and NLCD, there is the potential for differences in area estimates in states where specific land-use conversions into forest land do not exist in the FIA data. These difference in area estimates may result in differences between the summed estimates for mineral soil carbon stock changes across all states and the estimates reported in Table 6-31 through Table 6-34. Work is underway to integrate the dense time series of remotely sensed data into a new estimation system, which will facilitate land conversion estimation over the entire time series.

6.4 Cropland Remaining Cropland (CRT Category 4B1)

Carbon in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, carbon storage in cropland biomass and dead organic matter is relatively ephemeral and does not need to be reported according to the IPCC (2006), with the exception of carbon stored in perennial woody crop biomass, such as citrus groves and apple orchards, in addition to the biomass, downed wood and dead organic matter in agroforestry systems. Within soils, carbon is found in organic and inorganic forms of carbon, but soil organic carbon is the main source and sink for atmospheric CO_2. IPCC (2006) recommends reporting changes in soil organic carbon stocks due to agricultural land use and management activities for mineral and organic soils.[38]

Well-drained mineral soils typically contain from 1 to 6 percent organic carbon by weight, whereas mineral soils with high water tables for substantial periods of a year may contain significantly more carbon (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the soil organic carbon to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of carbon loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, application of biosolids (i.e., treated sewage sludge) and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net carbon stock change (Paustian et al. 1997a; Lal 1998; Conant et al. 2001; Ogle et al. 2005; Griscom et al. 2017; Ogle et al. 2019). Eventually, the soil can reach a new equilibrium that reflects a balance

[38] Carbon dioxide emissions associated with liming and urea application are also estimated but are included in the Liming and Urea Fertilization sections of the Agriculture chapter of the *Inventory*.

between carbon inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and carbon loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as histosols, include all soils with more than 12 to 20 percent organic carbon by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions.[39] Due to the depth and richness of the organic layers, carbon loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production leads to higher carbon loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland remaining cropland includes all cropland in an inventory year that has been cropland for a continuous time period of at least 20 years. This determination is based on the United States Department of Agriculture (USDA) National Resources Inventory (NRI) for non-federal lands (USDA-NRCS 2020) and the National Land Cover Dataset for federal lands (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land that is used to produce food and fiber, forage that is harvested and used as feed (e.g., hay and silage), in addition to cropland that has been enrolled in the Conservation Reserve Program (CRP)[40] (i.e., considered set-aside cropland).

There are two discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for cropland remaining cropland. First, croplands in Alaska are not included in the *Inventory*, and second, some miscellaneous croplands that occur throughout the United States are also not included in the *Inventory* due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). These differences lead to discrepancies between the managed area in cropland remaining cropland and the cropland area included in the *Inventory* analysis (Table 6-39). Improvements are underway to incorporate croplands in Alaska and miscellaneous croplands as part of future *Inventories* (see Planned Improvements section).

Land use and land management of mineral soils are the largest contributor to total net carbon stock change, especially in the early part of the time series (see Table 6-36 and Table 6-37). In 2022, mineral soils are estimated to sequester 62.0 MMT CO_2 Eq. (16.9 MMT C). This level of carbon storage in mineral soils represents a more than 58 percent increase since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 30.3 MMT CO_2 Eq. (8.3 MMT C) in 2022, which is an 11 percent decrease in losses of soil carbon compared to 1990. In total, United States agricultural soils in cropland remaining cropland sequestered approximately 31.7 MMT CO_2 Eq. (8.6 MMT C) in 2022.

Table 6-36: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(39.2)	(61.8)	(47.1)	(48.5)	(38.2)	(62.2)	(62.0)
Organic Soils	34.2	30.2	29.3	29.1	29.4	30.2	30.3

[39] N_2O emissions from drained organic soils are included in the Agricultural Soil Management section of the Agriculture chapter of the *Inventory*.

[40] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

Total Net Flux	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-37: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(10.7)	(16.9)	(12.9)	(13.2)	(10.4)	(17.0)	(16.9)
Organic Soils	9.3	8.2	8.0	7.9	8.0	8.2	8.3
Total Net Flux	**(1.4)**	**(8.6)**	**(4.9)**	**(5.3)**	**(2.4)**	**(8.7)**	**(8.6)**

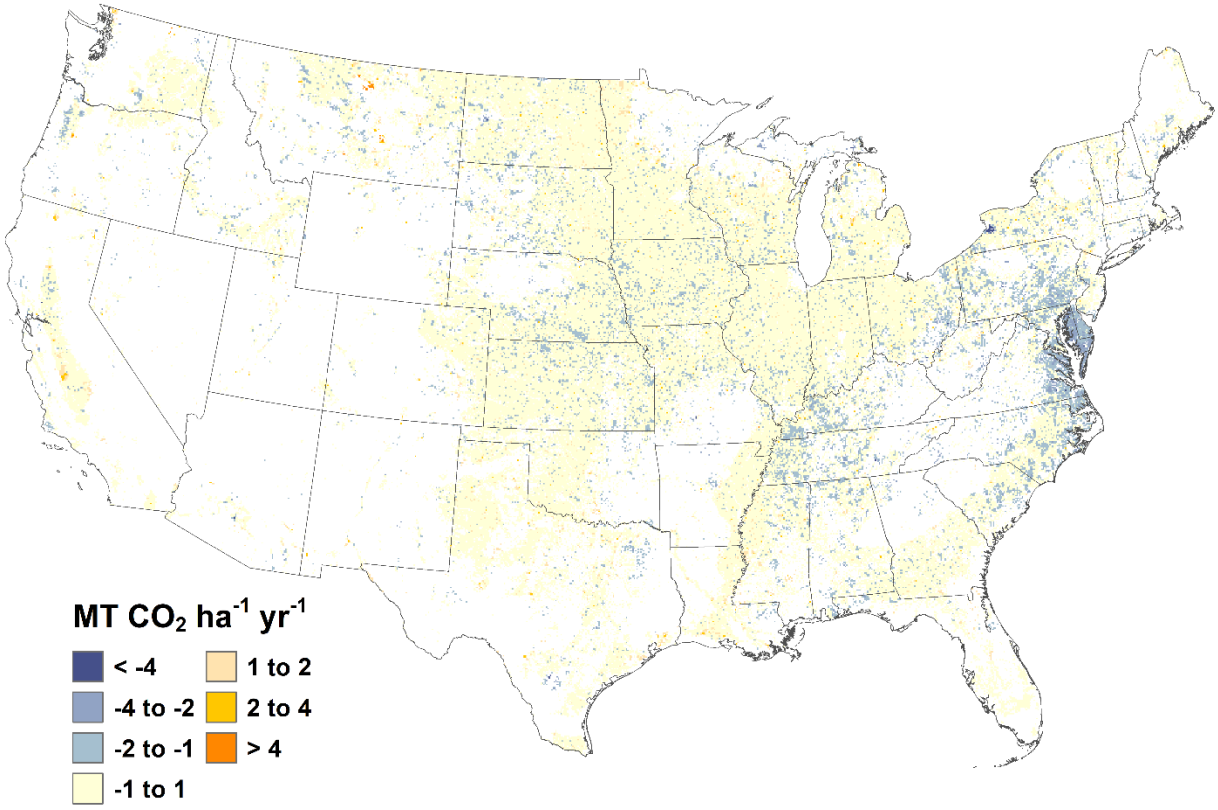
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Soil organic carbon stocks increase in cropland remaining cropland largely due to conservation tillage (i.e., reduced- and no-till practices), land set-aside from production in the Conservation Reserve Program, annual crop production with hay or pasture in rotations, and manure amendments (Ogle et al. 2023). The mineral soil carbon stock changes between 1990 and 2022 range from 38.2 to 69.6 MMT CO_2 Eq. per year, with a mean of 55.9 MMT CO_2 Eq. Soil organic carbon losses from drainage of organic soils are relatively stable across the time series with a mean emission of 30.2 MMT CO_2 Eq. per year.

The spatial variability in the 2020 annual soil organic carbon stock changes[41] are displayed in Figure 6-6 and Figure 6-7 for mineral and organic soils, respectively. Isolated areas with high rates of carbon accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas, such as the Maryland, Delaware, and Virginia where there have been relatively high adoption rates of cover crop management. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida and Louisiana), Northeast and upper Midwest surrounding the Great Lakes, and isolated areas along the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

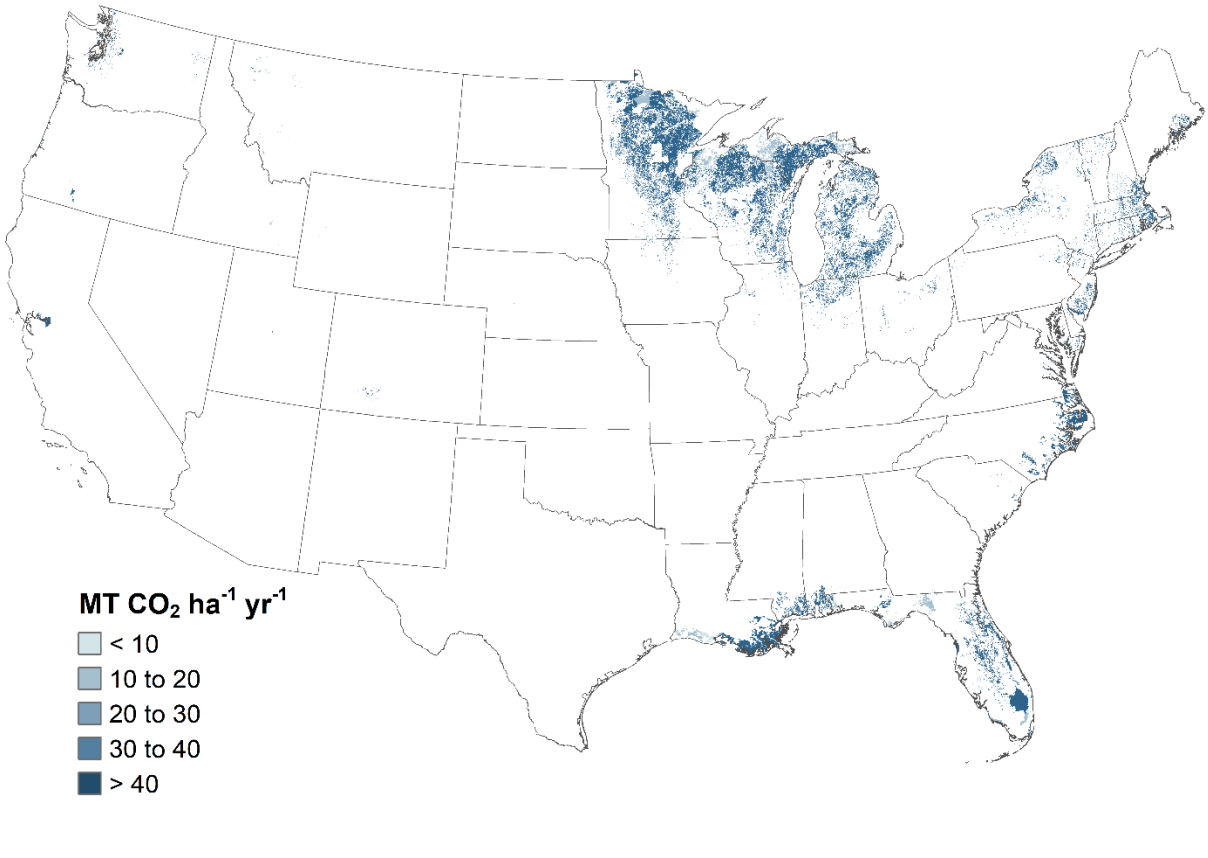
[41] Only national-scale emissions are estimated for 2021 to 2022 in this *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 6-6: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-7: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in soil organic carbon stocks for cropland remaining cropland, including (1) agricultural land use and management activities on mineral soils; and (2) agricultural land use and management activities on organic soils. Carbon dioxide emissions and removals[42] due to changes in mineral soil organic carbon stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010, 2023). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see list of crops in the Mineral Soil Carbon Stock Changes section below) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale, regardless of crop). Emissions from organic soils are estimated using a Tier 2 IPCC method. While a combination of Tier 2 and 3 methods are used to estimate carbon stock changes across most of the time series, a surrogate data method has been applied to

[42] Removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil carbon pools.

estimate stock changes in the last two years of the *Inventory*. Stock change estimates based on surrogate data will be recalculated in a future *Inventory* report using the Tier 2 and 3 methods when data become available.

Soil organic carbon stock changes on non-federal lands are estimated for cropland remaining cropland (as well as agricultural land falling into the IPCC categories land converted to cropland, grassland remaining grassland, and land converted to grassland) according to land-use histories recorded in the USDA NRI survey through 2017 (USDA-NRCS 2020), and the cropping histories were extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land-use areas are consistent across all land- use categories (see Section 6.1 for more information).

The NRI is a statistically-based sample and includes approximately 604,000 survey locations in agricultural land for the conterminous United States and Hawaii. There are 364,333 survey locations that are included in the Tier 3 method, and another 239,757 locations included in the Tier 2 method. Each survey location is associated with a weight that allows scaling of carbon stock changes from NRI survey locations to the entire country (i.e., each weight represents the amount of area that is expected to have the same land use/management history as the sample point).

Land use and some management information (e.g., crop type, soil attributes, and irrigation) are collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data has been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018 to 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), by overlaying NRI survey locations on the CDL in a geographic information system and extracting the crop types to extend the cropping histories. NRI survey locations are classified as cropland remaining cropland in a given year between 1990 and 2020 if the land use has been cropland for a continuous time period of at least 20 years. The NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of cropland remaining cropland in the early part of the time series to the extent that some areas are converted to cropland between 1971 and 1978.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate organic carbon stock changes for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat, but is not applied to estimate organic carbon stock changes from other crops or rotations with other crops. The model-based approach uses the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil organic carbon stock changes, soil nitrous oxide (N_2O) emissions from agricultural soil management, and methane (CH_4) emissions from rice cultivation. Carbon and nitrogen dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil carbon and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between carbon and nitrogen cycling in soils.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and soil organic carbon stock changes on federal croplands. Mineral soil organic carbon stocks are estimated using a Tier 2 method for these areas because the DayCent model, which is used for the Tier 3 method, has not been fully tested for estimating carbon stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands using DayCent.

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 stock change data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[43] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 for more information about the surrogate data method. Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data.

Box 6-4: Surrogate Data Method

Time series extension is needed because there are typically gaps at the end of the time series. This is mainly because the NRI, which provides critical data for estimating greenhouse gas emissions and removals, does not release new activity data every year.

A surrogate data method has been used to impute missing emissions at the end of the time series for soil organic carbon stock changes in cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland. A linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2020 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), Xβ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the emissions data for 1990 to 2020 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2021 to 2022.

A critical issue with the application of splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions rather than compiling the full inventory. Consequently, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each iteration of the Monte Carlo analysis for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2020), estimating emissions from each model and deriving confidence intervals combining uncertainty across all iterations. This approach propagates uncertainties through the calculations from the original inventory and the surrogate data method. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes are estimated to a 30 cm depth using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of carbon, nitrogen, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g.,

[43] See https://quickstats.nass.usda.gov/.

planting, harvesting, fertilization, manure amendments, tillage, irrigation, cover crops, and grazing; more information is provided below). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands[44] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2022), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-5 for additional information).

Box 6-5: Tier 3 Approach for Soil Carbon Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil organic carbon stock changes for the majority of agricultural land with mineral soils. This approach results in a more complete and accurate estimation of soil organic carbon stock changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

1) The IPCC Tier 1 and 2 methods are simplified approaches for estimating soil organic carbon stock changes and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.

2) The IPCC Tier 1 and 2 methods have a coarser spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 combinations in the United States. In contrast, the Tier 3 model simulates soil carbon dynamics at about 364,000 individual NRI survey locations in crop fields and grazing lands.

The IPCC Tier 1 and 2 methods use a simplified approach for estimating changes in carbon stocks that assumes a step-change from one equilibrium level of the carbon stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of carbon stock changes that may reach a new equilibrium over an extended period of time depending on the environmental conditions (i.e., a new equilibrium often requires hundreds to thousands of years to reach). More specifically, the DayCent model, which is used in the United States Inventory, simulates soil carbon dynamics (and CO_2 emissions and uptake) on a daily time step based on carbon emissions and removals from plant production and decomposition processes. These changes in soil organic carbon stocks are influenced by multiple factors that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2020). Additional sources of activity data are used to supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-

[44] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2020. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006 and 2013 to 2016. These data are combined with other datasets in an imputation analysis. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use Gradient Boosting (Friedman 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988; van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. It makes the best predictions at specific NRI survey locations or at state or region level models. The predictive mean matching method identifies the most similar management activity recorded in the CEAP surveys that match the prediction from the gradient boosting algorithm. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the gradient boosting. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2020). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). To determine the trends in tillage management, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and OpTIS Data Product[45] for 2008 to 2020 (Hagen et al. 2020). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). For cover crops, CEAP data are combined with information from USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS data (Hagen et al. 2020). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

Uncertainty in the carbon stock estimates from DayCent associated with management activity includes input uncertainty due to missing management data in the NRI survey, which is imputed from other sources as discussed above; model uncertainty due to incomplete specification of carbon and nitrogen dynamics in the DayCent model algorithms and associated parameterization; and sampling uncertainty associated with the statistical design of the NRI survey. Uncertainty is estimated with two variance components (Ogle et al. 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007, 2010, 2023). The data are combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2020. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), and random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the DayCent model. Further elaboration on the methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

[45] OpTIS data on tillage and cover crop practices provided by Regrow Agriculture, Inc.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). The time series of activity data will be updated in a future inventory, and emissions from 2021 to 2022 will be recalculated.

Tier 2 Approach. In the IPCC Tier 2 method, data on climate, soil types, land use, and land management activity are used to classify land area and apply appropriate factors to estimate soil organic carbon stock changes to a 30 cm depth (Ogle et al. 2003, 2006). The primary source of activity data for land use, crop and irrigation histories is the 2017 NRI survey (USDA-NRCS 2020). Each NRI survey location is classified by soil type, climate region, and management condition using data from other sources. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled for these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Therefore, land-use patterns for the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015).

Additional management activities needed for the Tier 2 method are based on the imputation product described for the Tier 3 approach, including tillage practices, mineral fertilization, and manure amendments that are assigned to NRI survey locations. Activity data used exclusively in the Tier 2 method are wetland restoration for Conservation Reserve Program land from Euliss and Gleason (2002). Climate zones in the United States are determined from the IPCC climate map (IPCC 2006), and then assigned to NRI survey locations.

Reference carbon stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provides a more robust sample for estimating the reference condition. Country-specific carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon storage (Ogle et al. 2003, 2006). The factors represent changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. However, country-specific factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts of this practice. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Uncertainty in soil carbon stock changes is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and carbon stock change factors. To assess this uncertainty, changes in soil organic carbon stocks for mineral soils are estimated 1,000 times for 1990 through 2020 using a Monte Carlo stochastic simulation approach and probability distribution functions for the country-specific stock change factors, reference carbon stocks, and land use activity data (Ogle et al. 2003; Ogle et al. 2006). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC

2006). As with the Tier 3 method, time series of activity data will be updated in a future inventory, and emissions from 2021 to 2022 will be recalculated (see Planned Improvements section).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in cropland remaining cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) rather than default IPCC rates. As with mineral soils, uncertainty is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and emission factors. A Monte Carlo stochastic simulation with 1,000 iterations is used to quantify this uncertainty with probability distribution functions for the country-specific organic soil emission factors and land use activity data. The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. Further elaboration on the methodology and data used to estimate stock changes from organic soils are described in Annex 3.12.

In order to ensure time-series consistency, the same Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in a future inventory when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is quantified for changes in soil organic carbon stocks associated with cropland remaining cropland (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-38 for each subsource (mineral and organic soil carbon stocks) and the methods that are used in the *Inventory* analyses (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived from two variance components (Ogle et al. 2010). For the first component, a Monte Carlo approach is used to address uncertainties in management activity data as well as model parameterization and structure or emissions factors for the Tier 3 and Tier 2 methods, respectively (Ogle et al. 2010, 2023). The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire land base, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities (see Annex 3.12 for further discussion). For 2021 to 2022, additional uncertainty is propagated through a Monte Carlo analysis that is associated with the surrogate data method (see Box 6-3). Soil organic carbon stock changes from the Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic carbon stocks in cropland remaining cropland ranges from 212 percent below to 212 percent above the 2022 stock change estimate of -31.7 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error.

Table 6-38: Approach 2 Quantitative Uncertainty Estimates for Soil Carbon Stock Changes occurring within Cropland Remaining Cropland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(58.8)	(123.6)	5.9	-110%	+110%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.2)	(8.4)	2.0	-162%	+162%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	30.3	12.7	47.9	-58%	+58%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(31.7)**	**(99.0)**	**35.6**	**-212%**	**+212%**

[a] Range of C stock change estimates is a 95 percent confidence interval.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of agricultural woody biomass and dead organic matter carbon stock changes. However, woody biomass carbon stock changes are likely minor in perennial crops, with relatively small amounts of woody crops such as orchards and nut plantations. There will be removal and replanting of tree crops each year, but the net effect on biomass carbon stock changes is probably minor because the overall area and tree density is relatively constant across time series. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have more significant changes over the *Inventory* time series, compared to perennial woody crops, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter carbon stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. This trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. In addition, results from the DayCent model are compared to field measurements and soil monitoring sites associated with the NRI (Spencer et al. 2011), and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model (Ogle et al. 2007). The comparisons include 69 long-term experiment sites and 145 NRI soil monitoring network sites, with 1406 observations across all of the sites (see Annex 3.12 for more information). Quality control uncovered several errors in the Tier 2 method following the initial analysis, such as no estimation for some NRI survey locations (i.e., federal lands and Hawaii), double counting some NRI survey locations with aggregation to the national scale, and errors in the estimation of the two variance components associated with the uncertainty analysis. The errors have been corrected following the diagnosis of the quality control issues.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, and

planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g) constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; and i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method. The combined impact from these improvements resulted in an average annual increase in soil C stocks of 4.2 MMT CO_2 Eq., or 26 percent, from 1990 to 2021 relative to the previous *Inventory*.

Planned Improvements

A key improvement is conducting an analysis of carbon stock changes in Alaska for cropland. The improvement will be conducted using the Tier 2 method for mineral and organic soils that is described earlier in this section. The analysis will initially focus on land-use change, which typically has a larger impact on soil organic carbon stock changes than management practices, but will be further refined over time to incorporate management data. The improvement will resolve most of the differences between the managed land base for cropland remaining cropland and amount of area currently included in cropland remaining cropland (see Table 6-39).

Table 6-39: Comparison of Managed Land Area in Cropland Remaining Cropland and Area in the Current Cropland Remaining Cropland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	*Inventory*	Difference
1990	162,273	162,247	26
1991	161,840	161,814	26
1992	161,343	161,317	26
1993	159,577	159,551	26
1994	157,890	157,864	26
1995	157,277	157,251	26
1996	156,639	156,613	26
1997	156,018	155,992	26
1998	152,335	152,309	26
1999	151,432	151,406	26
2000	151,257	151,231	26
2001	150,734	150,708	26
2002	150,426	150,400	26
2003	151,055	151,029	26
2004	150,787	150,761	26
2005	150,417	150,391	26
2006	149,908	149,882	26
2007	150,117	150,091	26
2008	149,718	149,692	26
2009	149,660	149,634	26
2010	149,222	149,196	26
2011	148,626	148,600	26
2012	148,297	148,271	26
2013	148,660	148,633	26
2014	149,141	149,115	26
2015	148,525	148,499	26
2016	148,436	148,410	26

2017	148,331	148,305	26
2018	149,720	149,694	26
2019	149,503	149,477	26
2020	149,822	149,796	26
2021	150,591	*	*
2022	151,276	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

There are several other planned improvements underway related to the plant production module in DayCent. Crop parameters associated with temperature effects on plant production will be further improved in DayCent with additional model calibration. Senescence events following grain filling in crops, such as wheat, are being modified based on recent model algorithm development, and will be incorporated. There will also be further testing and parameterization of the DayCent model to reduce uncertainty, particularly the submodules that are used to approximate the cycling of nitrogen through the plant-soil system, which will also have impacts on carbon cycling in the model simulations.

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that are used in the field burning of agricultural residues source category (see Section 5.7). This improvement will more accurately represent the carbon inputs to the soil that are associated with residue burning. In addition, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Another improvement is to estimate biomass carbon stock changes in agroforestry systems and perennial tree crops. Methods combining survey data and remote sensing imagery are under development to determine the extent of land with agroforestry and perennial tree crops. In addition, a meta-analysis is being conducted to derive country-specific factors for biomass C stock changes in agroforestry systems. Although the influence of perennial tree crop biomass is expected to be minor, carbon stock changes may be significantly impacted by the effect of agroforestry practices.

Many of these improvements are expected to be completed for the next (1990 through 2023) *Inventory* (i.e., 2025 submission), pending prioritization of resources.

6.5 Land Converted to Cropland (CRT Category 4B2)

Land converted to cropland includes all current cropland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006), and used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage). For example, grassland or forest land converted to cropland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006).

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983; Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon stocks with land use change. All soil organic carbon stock changes are estimated and reported for land converted to cropland, but reporting of carbon stock changes for aboveground and belowground biomass, dead wood, and litter pools is limited to forest land converted to cropland and grassland converted to cropland for woodland conversions (i.e., woodland conversion to cropland).[46]

Grassland converted to cropland is the largest source of emissions from 1990 to 2000, while forest land converted to cropland is the largest source of emissions from 2001 to 2022. This shift is largely due to reduced losses of carbon from mineral soils after 2001. The high losses of carbon from forest land converted to cropland is due to reductions in biomass and dead organic matter carbon following conversion from forests (Table 6-40 and Table 6-41). The net change in total carbon stocks for 2022 led to CO_2 emissions to the atmosphere of 35.1 MMT CO_2 Eq. (9.6 MMT C), including 12.1 MMT CO_2 Eq. (3.3 MMT C) from aboveground biomass carbon losses, 2.0 MMT CO_2 Eq. (0.6 MMT C) from belowground biomass carbon losses, 2.3 MMT CO_2 Eq. (0.6 MMT C) from dead wood carbon losses, 3.4 MMT CO_2 Eq. (0.9 MMT C) from litter carbon losses, 12.6 MMT CO_2 Eq. (3.4 MMT C) from mineral soils and 2.7 MMT CO_2 Eq. (0.7 MMT C) from drainage and cultivation of organic soils. The overall net loss of carbon has declined by 23 percent from 1990 to 2022.

Table 6-40: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland by Land-Use Change Category (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**27.3**	**17.2**	**13.7**	**13.0**	**10.6**	**16.1**	**16.3**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	24.6	13.7	10.7	10.1	8.0	13.5	13.6
Organic Soils	2.4	3.3	2.7	2.7	2.4	2.4	2.4
Forest Land Converted to Cropland	**19.2**	**19.2**	**19.7**	**19.7**	**19.7**	**19.6**	**19.6**
Aboveground Live Biomass	11.4	11.6	11.9	11.9	11.9	11.9	11.9
Belowground Live Biomass	1.9	2.0	2.0	2.0	2.0	2.0	2.0
Dead Wood	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Litter	3.2	3.3	3.3	3.4	3.4	3.4	3.4
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.1	+	+	+	+	+	+
Other Lands Converted to Cropland	**(1.8)**	**(2.5)**	**(1.6)**	**(1.6)**	**(1.2)**	**(1.1)**	**(1.1)**
Mineral Soils	(1.9)	(2.6)	(1.7)	(1.6)	(1.2)	(1.1)	(1.1)
Organic Soils	0.1	0.1	+	+	+	+	+
Settlements Converted to Cropland	**(0.0)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.7**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Mineral Soils	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Organic Soils	0.5	0.5	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**11.6**	**11.7**	**12.0**	**12.0**	**12.1**	**12.1**	**12.1**
Belowground Live Biomass	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Dead Wood	**2.2**	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**

[46] Changes in biomass carbon stocks are estimated for forest land converted to cropland and grassland converted to cropland for woodland conversions. There is a planned improvement to include the effect of other land use conversions, in addition to herbaceous grassland conversions to cropland in a future *Inventory*. Note: changes in dead organic matter are assumed negligible for other land use conversions to cropland, except forest land and woodland conversions.

Litter	**3.3**	**3.3**	**3.4**	**3.4**	**3.4**	**3.4**	**3.4**
Total Mineral Soil Flux	**23.2**	**11.3**	**9.2**	**8.6**	**6.9**	**12.5**	**12.6**
Total Organic Soil Flux	**3.2**	**3.9**	**3.0**	**3.0**	**2.6**	**2.6**	**2.7**
Total Net Flux	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-41: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**7.4**	**4.7**	**3.7**	**3.6**	**2.9**	**4.4**	**4.4**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	6.7	3.7	2.9	2.8	2.2	3.7	3.7
Organic Soils	0.7	0.9	0.7	0.7	0.6	0.6	0.7
Forest Land Converted to Cropland	**5.2**	**5.2**	**5.4**	**5.4**	**5.4**	**5.4**	**5.4**
Aboveground Live Biomass	3.1	3.2	3.2	3.3	3.3	3.3	3.3
Belowground Live Biomass	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Dead Wood	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Litter	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Mineral Soils	0.1	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Cropland	**(0.5)**	**(0.7)**	**(0.4)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**
Mineral Soils	(0.5)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Cropland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	0.1	0.1	+	+	+	+	+
Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**3.2**	**3.2**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**
Belowground Live Biomass	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Total Mineral Soil Flux	**6.3**	**3.1**	**2.5**	**2.4**	**1.9**	**3.4**	**3.4**
Total Organic Soil Flux	**0.9**	**1.1**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**
Total Net Flux	**12.4**	**9.4**	**8.7**	**8.6**	**8.0**	**9.5**	**9.6**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to cropland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with conversion of forest lands to croplands, as well as (2) the impact from all land use conversions to cropland on mineral and soil organic carbon stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter carbon stock changes for forest land converted to cropland. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023). However, there is no country-specific data for cropland biomass, so only a default biomass estimate (IPCC 2006) for croplands was used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon density estimates exist for croplands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023). If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

For dead organic matter, if FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011; Westfall et al. 2023) with additional modifications for woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic stock changes are estimated for land converted to cropland according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2017 (USDA-NRCS 2020), and the time series for cropping histories was extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as land converted to cropland in a given year between 1990 and 2020 if the land use is cropland but had been another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998, which may have led to an underestimation of land converted to cropland in the early part of the time series to the extent that some areas are converted to cropland from 1971 to 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach using the DayCent ecosystem model (Ogle et al. 2010, 2023) is applied to estimate carbon stock changes from 1990 to 2020 for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat. Soil organic carbon stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003, 2006), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[47]

For the years 2021 to 2022, a surrogate data method is used to estimate soil organic carbon stock changes at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 stock change data from the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[48] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 in the Methodology section of Cropland Remaining Cropland for more information about the surrogate data method. Stock change estimates for 2021 to 2022 will be recalculated in future *Inventories* when the time series of activity data are updated.

Tier 3 Approach. For the Tier 3 method, mineral soil organic carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates are obtained by using the model to simulate historical land use change patterns as recorded in the USDA NRI survey (USDA-NRCS 2020). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. See the cropland remaining cropland section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (described in Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Time series of activity data will be updated in a future *Inventory*, and emissions from 2020 to 2022 will be recalculated.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic carbon stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in cropland remaining cropland. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the 2021 to 2022 time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future *Inventory*, and emissions from 2021 to 2022 will be recalculated.

[47] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2018).

[48] See https://quickstats.nass.usda.gov/.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) as described in the cropland remaining cropland section for organic soils. Further elaboration on the methodology is also provided in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in a future *Inventory* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to cropland and grassland converted to cropland for woodland conversions are conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux associated with forest land remaining forest land. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method, which is also described in cropland remaining cropland.

Uncertainty estimates are presented in Table 6-42 for each sub-source (i.e., biomass carbon stocks, dead wood carbon stocks, litter carbon stocks, soil organic carbon stocks for mineral and organic soils) and the method applied in the *Inventory* analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates for the total carbon stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006). The combined uncertainty for total carbon stock changes in land converted to cropland ranged from 93 percent below to 93 percent above the 2022 stock change estimate of 35.1 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-42: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Cropland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**16.3**	**(12.1)**	**44.7**	**-174%**	**174%**
Aboveground Live Biomass	0.1	+	0.3	-128%	124%
Belowground Live Biomass	+	+	+	-100%	56%
Dead Wood	+	+	0.1	-100%	173%
Litter	+	+	0.1	-100%	147%
Mineral Soil C Stocks: Tier 3	11.0	(17.2)	39.3	-256%	256%
Mineral Soil C Stocks: Tier 2	2.6	0.6	4.5	-77%	77%

Organic Soil C Stocks: Tier 2	2.4	0.5	4.4	-79%	79%
Forest Land Converted to Cropland	**19.6**	**3.4**	**35.8**	**-82%**	**82%**
Aboveground Live Biomass	11.9	(3.2)	27.1	-127%	127%
Belowground Live Biomass	2.0	(0.6)	4.6	-127%	127%
Dead Wood	2.2	(0.6)	5.1	-128%	127%
Litter	3.4	(0.9)	7.6	-127%	128%
Mineral Soil C Stocks: Tier 2	0.1	+	0.2	-107%	107%
Organic Soil C Stocks: Tier 2	+	+	0.1	-429%	429%
Other Lands Converted to Cropland	**(1.1)**	**(2.1)**	+	**-99%**	**99%**
Mineral Soil C Stocks: Tier 2	(1.1)	(2.1)	+	-99%	99%
Organic Soil C Stocks: Tier 2	+	+	+	0%	0%
Settlements Converted to Cropland	**(0.1)**	**(0.3)**	+	**-97%**	**97%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	(0.1)	-71%	71%
Organic Soil C Stocks: Tier 2	+	+	0.1	-103%	103%
Wetlands Converted to Croplands	**0.4**	**(0.1)**	**0.8**	**-115%**	**115%**
Mineral Soil C Stocks: Tier 2	0.2	+	0.3	-124%	124%
Organic Soil C Stocks: Tier 2	0.2	(0.2)	0.6	-173%	173%
Total: Land Converted to Cropland	**35.1**	**2.4**	**67.8**	**-93%**	**93%**
Aboveground Live Biomass	**12.1**	**(3.1)**	**27.2**	**-126%**	**126%**
Belowground Live Biomass	**2.0**	**(0.5)**	**4.6**	**-126%**	**126%**
Dead Wood	**2.3**	**(0.6)**	**5.1**	**-126%**	**125%**
Litter	**3.4**	**(0.9)**	**7.7**	**-126%**	**126%**
Mineral Soil C Stocks: Tier 3	**11.0**	**(17.2)**	**39.3**	**-256%**	**256%**
Mineral Soil C Stocks: Tier 2	**1.6**	**(0.7)**	**3.8**	**-144%**	**144%**
Organic Soil C Stocks: Tier 2	**2.7**	**0.7**	**4.7**	**-73%**	**73%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with lack of reporting of agricultural biomass and dead organic matter carbon stock changes. Biomass carbon stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land that is used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to larger changes in biomass carbon stocks at least in some regions of the United States. However, there are currently no datasets to evaluate the trends. Changes in dead organic matter carbon stocks are assumed to be negligible with conversion of land to croplands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future *Inventory*.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland for information on QA/QC steps.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g)

constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method, and j) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to cropland. Finally, see further updates in Section 6.2, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to cropland estimates. As a result, land converted to cropland has an estimated smaller carbon loss of 20.7 MMT CO_2 Eq. on average over the time series. This represents a 37 percent average decrease in carbon stock change losses for land converted to cropland compared to the previous *Inventory*, and is mainly due to less loss of carbon associated with forest land converted to cropland.

Planned Improvements

A key improvement is to estimate the biomass carbon stock changes for other land use changes beyond only forest land converted to cropland and grassland converted to cropland for woodland conversion, which is included in the current *Inventory*. Additional planned improvements are discussed in the Planned Improvements section of Cropland Remaining Cropland.

6.6 Grassland Remaining Grassland (CRT Category 4C1)

Carbon in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of carbon in grasslands, and have the greatest potential for longer-term storage or release of carbon. Biomass and dead organic matter carbon pools are relatively ephemeral compared to the soil carbon pool, with the exception of carbon stored in tree and shrub biomass that occurs in grasslands. The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon stocks with land use and management. Carbon stock changes for aboveground and belowground biomass, dead wood and litter pools are reported for woodlands (i.e., a subcategory of grasslands[49]), and may be extended to include agroforestry management associated with grasslands in the future. For soil organic carbon, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes due to (1) agricultural land use and management activities on mineral soils, and (2) agricultural land use and management activities on organic soils.[50]

Grassland remaining grassland includes all grassland in an inventory year that had been grassland for a continuous time period of at least 20 years (USDA-NRCS 2018). Grassland includes pasture and rangeland that are primarily, but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or inter-seeding of legumes. Woodlands are also considered grassland and are areas of continuous tree cover that do not meet the definition of forest land (see Section 6.1 for more information about the criteria for forest land).

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for grassland remaining grassland. Specifically, grasslands in Alaska are not included in the *Inventory*, and this land base is approximately 50 million hectares. This difference leads to a discrepancy between

[49] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

[50] CO_2 emissions associated with liming and urea fertilization are also estimated but included in the Agriculture chapter of the report.

the managed area in grassland remaining grassland in the land representation and the grassland area included in the emissions and removals estimation for the grassland remaining grassland land-use category (Table 6-46). Improvements are underway to incorporate grasslands in Alaska as part of future *Inventories* (see Planned Improvements section).

For grassland remaining grassland, there has been considerable variation in carbon stocks between 1990 and 2022. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes are small on a per hectare rate basis across the time series even in the years with a larger total change in stocks. The net change in total carbon stocks for 2022 led to net CO_2 emissions to the atmosphere of 13.4 MMT CO_2 Eq. (3.6 MMT C), including -1.3 MMT CO_2 Eq. (-0.4 MMT C) from net gains of aboveground biomass C, -0.2 MMT CO_2 Eq. (-0.1 MMT C) from net gains in belowground biomass carbon, 2.8 MMT CO_2 Eq. (0.8 MMT C) from net losses in dead wood carbon, less than 0.05 MMT CO_2 Eq. (less than 0.05 MMT C) from net gains in litter C, 6.5 MMT CO_2 Eq. (1.8 MMT C) from net losses in mineral soil organic carbon, and 5.5 MMT CO_2 Eq. (1.5 MMT C) from losses of carbon due to drainage and cultivation of organic soils (Table 6-43 and Table 6-44). Losses of carbon are 45.2 percent lower in 2022 compared to 1990, but as noted previously, stock changes are highly variable from 1990 to 2022, with an average annual change of 19.9 MMT CO_2 Eq. (5.4 MMT C).

Table 6-43: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(2.7)	(2.1)	(1.4)	(1.4)	(1.4)	(1.4)	(1.3)
Belowground Live Biomass	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	3.2	3.1	2.9	2.9	2.9	2.9	2.8
Litter	(0.4)	(0.2)	+	+	+	+	+
Mineral Soils	18.6	18.6	22.0	22.0	9.3	3.8	6.5
Organic Soils	6.1	5.1	5.3	5.3	5.5	5.5	5.5
Total Net Flux	**24.4**	**24.1**	**28.6**	**28.5**	**16.1**	**10.6**	**13.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(0.7)	(0.6)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Belowground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	0.9	0.8	0.8	0.8	0.8	0.8	0.8
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	5.1	5.1	6.0	6.0	2.5	1.0	1.8
Organic Soils	1.7	1.4	1.4	1.4	1.5	1.5	1.5
Total Net Flux	**6.6**	**6.6**	**7.8**	**7.8**	**4.4**	**2.9**	**3.6**

+ Does not exceed 0.05 MMT C.

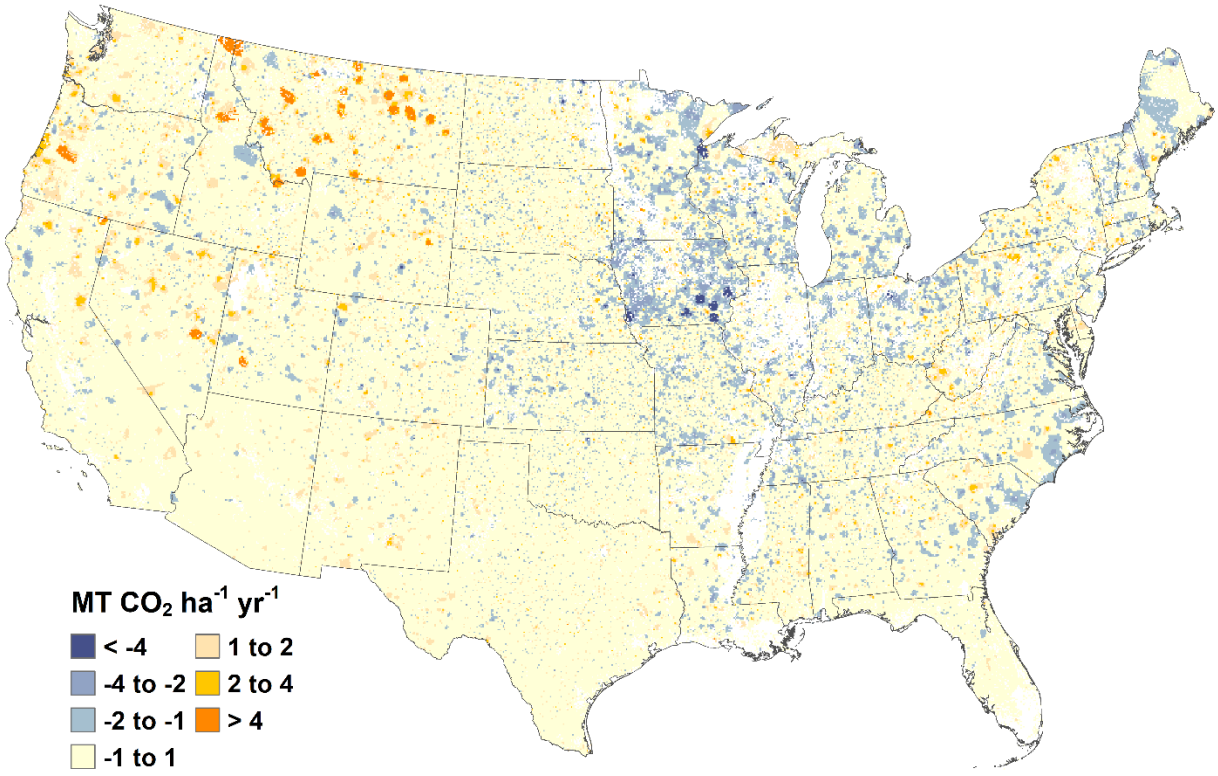
Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

The spatial variability in soil organic carbon stock changes for 2020[51] is displayed in Figure 6-8 for mineral soils and in Figure 6-9 for organic soils. Although relatively small on a per-hectare basis, grassland soils gained carbon in

[51] Only national-scale emissions are estimated for 2021 to 2022 in the current *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on land use data from 2020.

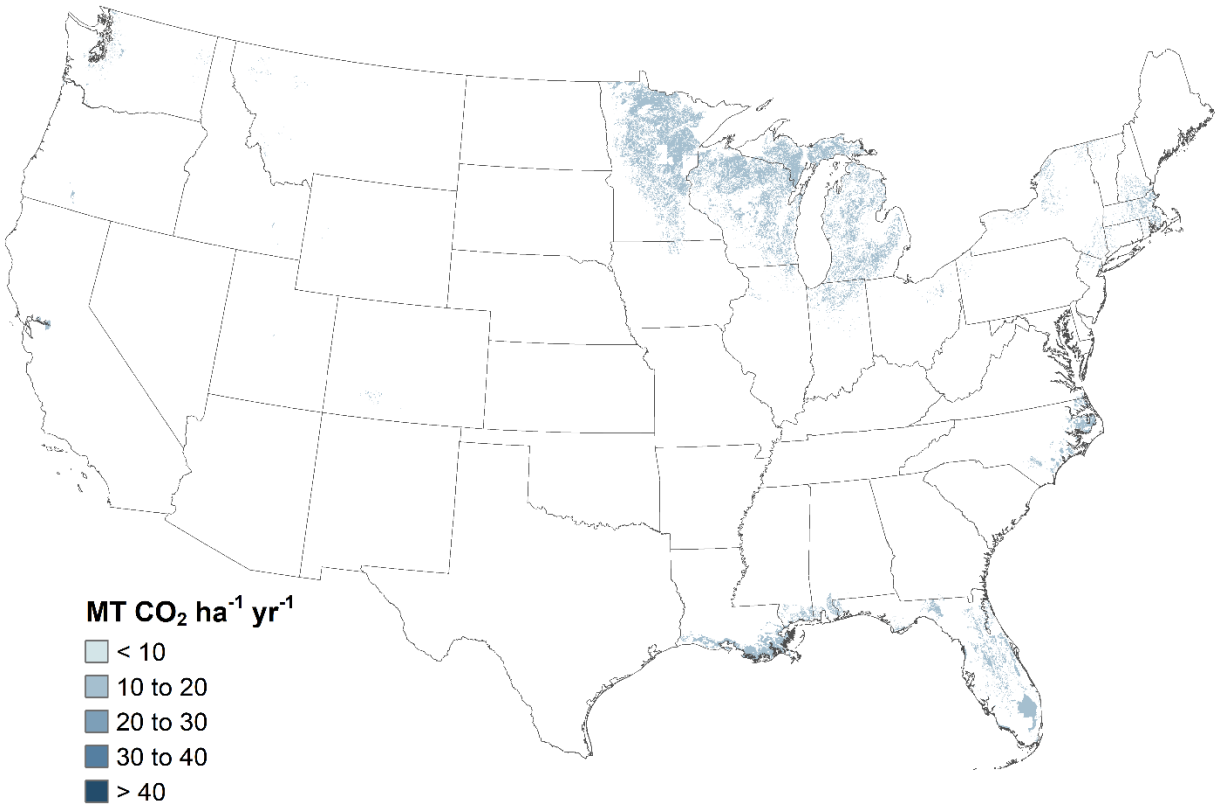
isolated areas that mostly occurred in pastures of the upper Midwest and eastern United States; losses occurred primarily in the northwestern region. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils that occur in managed grassland, including the Southeastern Coastal Region (particularly Florida), areas surrounding the Great Lakes in the upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

Figure 6-8: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-9: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 in the current *Inventory* using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2020.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for grassland remaining grassland, including (1) aboveground and belowground biomass, dead wood and litter carbon for woodlands, as well as (2) soil organic carbon stocks for mineral and organic soils.

Biomass, Dead Wood and Litter Carbon Stock Changes

Woodlands are lands that do not meet the definition of forest land or agroforestry (see Section 6.1), but include woody vegetation with carbon storage in aboveground and belowground biomass, dead wood and litter carbon (IPCC 2006) as described in the Forest Land Remaining Forest Land section. Carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon stocks and then subtracting the values between years to estimate the stock changes. The methods for estimating carbon stocks and stock changes for woodlands in grassland remaining grassland are consistent with those in the forest

land remaining forest land section and are described in Annex 3.13. All annual National Forest Inventory (NFI) plots available in the public FIA database (USDA Forest Service 2023) were used in the current *Inventory*. While the NFI is an all-lands inventory, only those plots that meet the definition of forest land are typically measured. However, in some cases, particularly in the Central Plains and Southwest United States, woodlands have been measured as part of the survey. This analysis is limited to those plots and is not considered a comprehensive assessment of trees outside of forest land that meet the definition of grassland. The same methods are applied from 1990 to 2022 in order to ensure time-series consistency. This methodology is consistent with IPCC guidance (2006).

Soil Carbon Stock Changes

The following section includes a brief description of the methodology used to estimate changes in soil organic carbon stocks for grassland remaining grassland, including: (1) agricultural land use and management activities on mineral soils; and (2) agricultural land use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils is provided in the Cropland Remaining Cropland section and Annex 3.12.

Soil organic carbon stock changes are estimated for grassland remaining grassland on non-federal lands according to land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2020). Land use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the data provided in the National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the NLCD are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as grassland remaining grassland in a given year between 1990 and 2020 if the land use had been grassland for 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of grassland remaining grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes from 1990 to 2020 for most mineral soils in grassland remaining grassland. The carbon stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume), as well as additional stock changes associated with biosolids (i.e., treated sewage sludge) amendments and federal land.[52]

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions data from the Tier 2 and 3 methods. Surrogate data for these regression models are based on weather data from the PRISM Climate Group (PRISM Climate Group 2022). See Box 6-4 in the Methodology section of Cropland Remaining Cropland for more information about the surrogate data method.

[52] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2020).

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes for grassland remaining grassland are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in Cropland Remaining Cropland. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2020). The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 and Annex 3.11. Manure nitrogen deposition from grazing animals (i.e., pasture/range/paddock (PRP) manure) is an input to the DayCent model to estimate the influence of PRP manure on carbon stock changes for lands included in the Tier 3 method. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the NRI survey data. Further elaboration on the Tier 3 methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Stock change estimates for 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data (see the Planned Improvements section in Cropland Remaining Cropland).

Tier 2 Approach. The Tier 2 approach is based on the same methods described in the Tier 2 portion of the Cropland Remaining Cropland section for mineral soils, with the exception of the manure nitrogen deposition from grazing animals (i.e., PRP manure), and the land use and management data that are used in the *Inventory* for federal grasslands. First, the PRP nitrogen manure is included in the Tier 2 method that is not deposited on lands included in the Tier 3 method. Second, the NRI (USDA-NRCS 2020) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. The land use data for federal lands is based on the NLCD (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grasslands, and compiles information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil organic carbon stock changes from federal grasslands, rangeland conditions in the BLM data are aligned with IPCC grassland management categories of nominal, moderately degraded, and severely degraded in order to apply the appropriate emission factors. Further elaboration on the Tier 2 methodology and data used to estimate carbon stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future *Inventory*, and emissions from 2021 to 2022 will be recalculated.

Additional Mineral Carbon Stock Change Calculations

A Tier 2 method is used to adjust annual carbon stock change estimates for mineral soils between 1990 and 2022 to account for additional carbon stock changes associated with biosolids (i.e., treated sewage sludge) amendments. Estimates of the amounts of biosolids nitrogen applied to agricultural land are derived from national data on biosolids generation, disposition, and nitrogen content (see Section 7.2 for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in grassland remaining grassland. Total biosolids generation data for 1988, 1996, and 1998, in dry mass units, are

obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. Nitrogen application rates from Kellogg et al. (2000) are used to determine the amount of area receiving biosolids amendments. The soil organic carbon storage rate is estimated at 0.38 metric tons carbon per hectare per year for biosolids amendments to grassland as described above. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in grassland remaining grassland are estimated using the Tier 2 method in IPCC (2006), which utilizes country-specific carbon loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the cropland remaining cropland section for organic soils and Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in cropland remaining cropland). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter carbon losses with woodlands is conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux associated with forest land remaining forest land. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Uncertainty analysis for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in Cropland Remaining Cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-45 for each subcategory (i.e., soil organic carbon stocks for mineral and organic soils) and the method applied in the *Inventory* analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The combined uncertainty for total carbon stock changes in grassland remaining grassland ranges from more than 926 percent below and above the 2022 stock change estimate of 13.4 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this data splicing method.

Table 6-45: Approach 2 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring Within Grassland Remaining Grassland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Woodland Biomass:					
Aboveground live biomass	(1.3)	(1.5)	(1.2)	-10%	12%
Belowground live biomass	(0.2)	(0.3)	(0.2)	-8%	8%
Dead wood	2.8	2.5	3.2	-13%	14%
Litter	+	+	0.1	-22%	22%
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	7.4	(116.1)	131.0	-1,663%	1,663%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	0.1	(0.4)	0.6	-448%	448%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Treated Sewage Sludge] Amendments)	(1.0)	(1.5)	(0.5)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.5	1.2	9.9	-79%	79%
Combined Uncertainty for Flux Associated with Carbon Stock Changes Occurring in Grassland Remaining Grassland	**13.4**	**(110.3)**	**137.0**	**-926%**	**926%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter carbon stock changes for agroforestry systems. Changes in biomass and dead organic matter carbon stocks are assumed to be negligible in other grasslands, largely comprised of herbaceous biomass, although there are significant changes at sub-annual time scales across seasons.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks in woodlands for grassland remaining grassland; c) constraining manure N applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. As a result of these improvements, grassland remaining grassland has a larger average loss of 10.7 MMT CO_2 Eq. across the time series compared to the previous *Inventory*, which is an 1,850 percent change on average over the time series. The large average value for the percentage change is due to an increase from near zero to 7.0 MMT CO_2 Eq. for the estimated carbon stock change in 1994.

Planned Improvements

A key improvement planned for the *Inventory* includes conducting an analysis of carbon stock changes for grasslands in Alaska. This improvement will be a significant development that will resolve the majority of the discrepancy between the managed land base for grassland remaining grassland and amount of area currently included in grassland remaining grassland emissions and removals calculations (see Table 6-46).

Table 6-46: Comparison of Managed Land Area in Grassland Remaining Grassland and the Area in the current Grassland Remaining Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	*Inventory*	Difference
1990	328,565	279,705	48,861
1991	328,058	279,205	48,853
1992	327,601	278,755	48,846
1993	325,869	277,030	48,839
1994	324,249	275,418	48,831
1995	323,373	274,549	48,824
1996	322,517	273,701	48,816
1997	321,752	272,944	48,808
1998	319,811	271,010	48,801
1999	318,903	270,110	48,793
2000	317,917	269,131	48,785
2001	317,060	268,282	48,778
2002	316,443	267,883	48,560
2003	316,545	268,206	48,340
2004	316,350	268,232	48,118
2005	315,930	268,034	47,897
2006	315,422	267,748	47,675
2007	315,164	267,712	47,452
2008	315,090	267,861	47,228
2009	315,163	268,159	47,005
2010	314,765	267,984	46,781
2011	314,270	267,712	46,557
2012	313,977	267,586	46,391
2013	314,640	268,416	46,224
2014	315,329	269,271	46,058
2015	315,427	269,535	45,891
2016	315,327	269,602	45,725
2017	316,056	270,339	45,717
2018	318,959	273,168	45,791
2019	320,255	274,471	45,784
2020	320,855	275,079	45,777
2021	321,909	*	*
2022	322,779	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

Additionally, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements. For information about

other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

Non-CO_2 Emissions from Grassland Fires (CRT Source Category 4C1)

Fires are common in grasslands and are thought to have been a key feature shaping the evolution of the grassland vegetation in North America (Daubenmire 1968; Anderson 2004). Fires can occur naturally through lightning strikes but are also an important management practice to remove standing dead vegetation and improve forage for grazing livestock. Woody and herbaceous biomass will be oxidized in a fire, although in this section the current focus is primarily on herbaceous biomass.[53] Biomass burning emits a variety of trace gases including non-CO_2 greenhouse gases such as CH_4 and N_2O, as well as CO and NO_x that can become greenhouse gases when they react with other gases in the atmosphere (Andreae and Merlet 2001). IPCC (2006) recommends reporting non-CO_2 greenhouse gas emissions from all wildfires and prescribed burning occurring in managed grasslands.

Biomass burning in grasslands of the United States (including burning emissions in grassland remaining grassland and land converted to grassland) is a relatively small source of emissions, but it has increased by 184 percent since 1990. In 2022, CH_4 and N_2O emissions from biomass burning in grasslands were 0.3 MMT CO_2 Eq. (12 kt) and 0.3 MMT CO_2 Eq. (1 kt), respectively. Annual emissions from 1990 to 2022 have averaged approximately 0.4 MMT CO_2 Eq. (14 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-47 and Table 6-48).

Table 6-47: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
CH_4	0.1	0.4	0.6	0.2	0.6	0.5	0.3
N_2O	0.1	0.4	0.5	0.2	0.5	0.4	0.3
Total Net Flux	**0.2**	**0.8**	**1.1**	**0.3**	**1.1**	**0.9**	**0.6**

Note: Totals may not sum due to independent rounding.

Table 6-48: CH_4, N_2O, CO, and NO_x Emissions from Biomass Burning in Grassland (kt)

	1990	2005	2018	2019	2020	2021	2022
CH_4	4	15	22	6	20	18	12
N_2O	+	1	2	1	2	2	1
CO	122	430	610	170	575	509	346
NO_x	7	26	37	10	35	31	21

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland, including (1) determination of the land base that is classified as managed grassland; (2) assessment of managed grassland area that is burned each year, and (3) estimation of emissions resulting from the fires. For this *Inventory*, the IPCC Tier 1 method is applied to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland from 1990 to 2020 (IPCC 2006). A data splicing method is used to estimate the emissions from 2021 to 2022, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the USDA National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA-NRCS 2020). NRI has survey locations across the entire United States, but does not

[53] A planned improvement is underway to incorporate woodland tree biomass into the *Inventory* for non-CO_2 emissions from grassland fires.

classify land use on federally-owned areas, and so survey locations on federal lands are designated as grassland using land cover data from the National Land Cover Dataset (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015) (see Section 6.1).

The area of biomass burning in grasslands (grassland remaining grassland and land converted to grassland) is determined using 30-m burned area data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2020 (MTBS 2023; Picotte, et al. 2020).[54] NRI survey locations on grasslands are designated as burned in a year if there is a fire within 500 m of the survey point according to the MTBS fire data. The area of biomass burning is estimated from the NRI spatial weights and aggregated to the country (Table 6-49).

Table 6-49: Thousands of Grassland Hectares Burned Annually

Year	1990	2005	2018	2019	2020	2021	2022
Thousand Hectares	457	1,612	2,290	637	2156	NE	NE

NE (Not Estimated)

Notes: Burned area was not estimated (NE) for 2021 to 2022, but will be updated in a future *Inventory*.

For 1990 to 2020, the total area of grassland burned is multiplied by the IPCC default factor for grassland biomass (4.1 tonnes dry matter per ha) (IPCC 2006) to estimate the amount of combusted biomass. A combustion factor of 1 is assumed in this *Inventory*, and the resulting biomass estimate is multiplied by the IPCC default grassland emission factors for CH_4 (2.3 g CH_4 per kg dry matter), N_2O (0.21 g N_2O per kg dry matter), CO (65 g CO per kg dry matter) and NO_x (3.9 g NO_x per kg dry matter) (IPCC 2006).

A linear extrapolation of the trend in the time series is applied to estimate emissions for 2021 to 2022. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to derive the trend in emissions over time from 1990 to 2020, and the trend is used to approximate the 2021 to 2022 emissions. The Tier 1 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

The same methods are applied from 1990 to 2020, and a data splicing method is used to extend the time series from 2021 to 2022 ensuring a consistent time series of emissions data. The trend extrapolation is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006).

Uncertainty

Emissions are estimated using a linear regression model with ARMA errors for 2021 to 2022. The model produces estimates for the upper and lower bounds of the emission estimate and the results are summarized in Table 6-50. Methane emissions from biomass burning in grassland for 2022 are estimated to be between approximately 0.0 and 0.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between approximately 0.0 and 0.7 MMT CO_2 Eq., or 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq.

[54] See http://www.mtbs.gov.

Table 6-50: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Burning	CH_4	0.3	+	0.8	-100%	+137%
Grassland Burning	N_2O	0.3	+	0.7	-100%	+137%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by linear regression time-series model for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of emissions from biomass burning in grasslands of Alaska. Grassland burning emissions could be relatively large in this region of the United States, and therefore extending this analysis to include Alaska is a planned improvement for the *Inventory*. There is also uncertainty due to lack of reporting on the combustion of woody biomass, and this is another planned improvement.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

While the methods for calculating non-CO_2 emissions from grassland burning remained the same, the two primary data sources have been updated from the previous *Inventory*. We used the current NRI 2017 dataset (USDA-NRCS 2020) and the current release of MTBS burn perimeter data (MTBS 2023). In the original estimation of non-CO_2 emissions, the same set of NRI survey locations was used for the entire time series, but the locations identified with burning were allowed to vary inter-annually with this revision. These changes resulted in a net increase in CO_2-equivalent emissions by an annual average of 0.1 MMT CO_2 Eq., or 19 percent from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Two key planned improvements have been identified for this source category, including 1) incorporation of country-specific grassland biomass factors, and 2) extending the analysis to include Alaska. In the current *Inventory*, biomass factors are based on a global default for grasslands that is provided by the IPCC (2006). There is considerable variation in grassland biomass, however, which would affect the amount of fuel available for combustion in a fire. Alaska has an extensive area of grassland and includes tundra vegetation, although some of the areas are not managed. There has been an increase in fire frequency in boreal forest of the region (Chapin et al. 2008), and this may have led to an increase in burning of neighboring grassland areas. There is also an effort under development to incorporate grassland fires into DayCent model simulations. Lastly, a future *Inventory* will incorporate non-CO_2 greenhouse emissions from burning woodland tree biomass in grasslands. These improvements are expected to reduce uncertainty and produce more accurate estimates of non-CO_2 greenhouse gas emissions from grassland burning.

6.7 Land Converted to Grassland (CRT Category 4C2)

Land converted to grassland includes all current grassland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006).[55] For example, cropland or forest land converted to grassland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes.

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983, Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic carbon stocks due to land use change. All soil organic carbon stock changes are estimated and reported for land converted to grassland, but there is limited reporting of other pools in this *Inventory*. Losses of aboveground and belowground biomass, dead wood and litter carbon from forest land converted to grassland are reported, as well as gains and losses associated with conversions to woodlands[56] from other land uses, including croplands converted to grasslands, settlements converted to grasslands and other lands converted to grasslands. However, the current *Inventory* does not include the gains and losses in aboveground and belowground biomass, dead wood and litter carbon for other land use conversions to grassland that are not woodlands.[57]

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for land converted to grassland. Specifically, grassland in Alaska is not included in the *Inventory*, and this leads to a difference between the managed area in land converted to grassland in the land representation and the grassland area included in the emissions and removal calculations for land converted to grassland (Table 6-54). Improvements are underway to incorporate grassland area in Alaska as part of future *Inventories* (see Planned Improvements section).

The largest carbon losses with land converted to grassland are associated with aboveground biomass, belowground biomass, and litter carbon losses from forest land converted to grassland (see Table 6-51 and Table 6-52). These three pools led to net emissions in 2022 of 31.3, 4.3, and 8.0 MMT CO_2 Eq. (8.5, 1.2, and 2.2 MMT C), respectively. The losses associated with forest land converted to grassland are partially offset by gains associated with other land converted to grassland and due to cropland converted to grassland, which leads to less intensive management of the soil. Drainage of organic soils for grassland management led to CO_2 emissions to the atmosphere of 1.4 MMT CO_2 Eq. (0.4 MMT C). The total net carbon stock change in 2022 for land converted to

[55] USDA NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of land converted to grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978.

[56] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

[57] Changes in biomass carbon stocks are not currently reported for other conversions to grassland (other than forest land conversion to grassland and other land-use conversions to woodlands), but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed negligible for other land use conversions (i.e., other than forest land) to grassland based on the Tier 1 method in IPCC (2006).

grassland is estimated as a loss of 25.6 MMT CO_2 Eq. (7.0 MMT C) or a net source of emissions, which represents a decrease in carbon stock loss by 27 percent compared to the initial reporting year of 1990.

Table 6-51: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(10.2)**	**(16.9)**	**(10.8)**	**(10.3)**	**(9.3)**	**(13.6)**	**(12.5)**
Aboveground Live Biomass	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	(10.4)	(18.1)	(11.7)	(11.1)	(10.1)	(14.4)	(13.3)
Organic Soils	0.6	1.4	1.1	1.1	1.0	1.0	1.0
Forest Land Converted to Grassland	**50.2**	**49.0**	**46.9**	**46.9**	**46.8**	**46.8**	**46.8**
Aboveground Live Biomass	34.5	33.4	31.8	31.8	31.8	31.8	31.8
Belowground Live Biomass	4.8	4.6	4.4	4.4	4.4	4.4	4.4
Dead Wood	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Litter	8.6	8.5	8.2	8.2	8.2	8.2	8.2
Mineral Soils	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland	**(4.0)**	**(9.6)**	**(10.2)**	**(10.5)**	**(8.2)**	**(8.0)**	**(8.0)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(3.8)	(9.4)	(10.1)	(10.4)	(8.1)	(7.9)	(7.9)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland	**(0.6)**	**(0.7)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**
Aboveground Live Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.1)	(0.3)	(0.5)	(0.5)	(0.4)	(0.4)	(0.4)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**(0.1)**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**33.9**	**32.9**	**31.4**	**31.4**	**31.3**	**31.3**	**31.3**
Belowground Live Biomass	**4.7**	**4.5**	**4.4**	**4.3**	**4.3**	**4.3**	**4.3**
Dead Wood	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**
Litter	**8.4**	**8.2**	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**
Total Mineral Soil Flux	**(14.6)**	**(27.9)**	**(22.4)**	**(22.1)**	**(18.7)**	**(22.8)**	**(21.7)**
Total Organic Soil Flux	**0.7**	**1.8**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**
Total Net Flux	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-52: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(2.8)**	**(4.6)**	**(3.0)**	**(2.8)**	**(2.5)**	**(3.7)**	**(3.4)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(2.8)	(4.9)	(3.2)	(3.0)	(2.8)	(3.9)	(3.6)
Organic Soils	0.2	0.4	0.3	0.3	0.3	0.3	0.3
Forest Land Converted to Grassland	**13.7**	**13.3**	**12.8**	**12.8**	**12.8**	**12.8**	**12.8**
Aboveground Live Biomass	9.4	9.1	8.7	8.7	8.7	8.7	8.7
Belowground Live Biomass	1.3	1.3	1.2	1.2	1.2	1.2	1.2
Dead Wood	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Litter	2.4	2.3	2.2	2.2	2.2	2.2	2.2
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Grassland	**(1.1)**	**(2.6)**	**(2.8)**	**(2.9)**	**(2.2)**	**(2.2)**	**(2.2)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(1.0)	(2.6)	(2.8)	(2.8)	(2.2)	(2.2)	(2.2)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Grassland	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**9.2**	**9.0**	**8.6**	**8.6**	**8.5**	**8.5**	**8.5**
Belowground Live Biomass	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**2.3**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Total Mineral Soil Flux	**(4.0)**	**(7.6)**	**(6.1)**	**(6.0)**	**(5.1)**	**(6.2)**	**(5.9)**
Total Organic Soil Flux	**0.2**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total Net Flux	**9.6**	**5.9**	**6.9**	**6.9**	**7.8**	**6.7**	**7.0**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to grassland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with forest land converted to grassland and other land use conversions to woodlands, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil organic carbon stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 3 method is applied to estimate biomass, dead wood and litter carbon stock changes for forest land converted to grassland. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023) and in the Eastern US, IPCC (2006) defaults for biomass in grasslands. There is limited data on grassland carbon stocks so only default biomass estimates (IPCC 2006) for grasslands were used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon density estimates exist for croplands) in the eastern United States. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

The amount of biomass carbon that is lost abruptly with forest land converted to grasslands is estimated based on the amount of carbon before conversion and the amount of carbon following conversion according to remeasurements in the FIA program. This approach is consistent with IPCC (2006) that assumes there is an abrupt change during the first year, but does not necessarily capture the slower change over the years following conversion until a new steady state is reached. It was determined that using an IPCC Tier 1 approach that assumes all carbon is lost in the year of conversion for forest land converted to grasslands in the West and Great Plains states does not accurately characterize the transfer of carbon in woody biomass during abrupt or gradual land use change. To estimate this transfer of carbon in woody biomass, state-specific carbon densities for woody biomass remaining on these former forest lands following conversion to grasslands were developed and included in the estimation of carbon stock changes from forest land converted to grasslands in the West and Great Plains states. A review of the literature in grassland and rangeland ecosystems (Asner et al. 2003; Huang et al. 2009; Tarhouni et al. 2016), as well as an analysis of FIA data, suggests that a conservative estimate of 50 percent of the woody biomass carbon density was lost during conversion from forest land to grasslands. This estimate was used to develop state-specific carbon density estimates for biomass, dead wood, and litter for grasslands in the West and Great Plains states, and these state-specific carbon densities were applied in the compilation system to estimate the carbon losses associated with conversion from forest land to grassland in the West and Great Plains states. Further, losses from forest land to what are often characterized as woodlands are included in this category using FIA plot remeasurements and the methods and models briefly described below and in detail in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). If FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011, Westfall et al. 2023) with additional modifications to woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011).

If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon density estimates for forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to grassland according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018 through 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), while survey locations identified as grasslands are assumed to not change over this time period. However, the areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information).

NRI survey locations are classified as land converted to grassland in a given year between 1990 and 2020 if the land use is grassland but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of land converted to grassland in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes in mineral soils for most of the area in land converted to grassland. Carbon stock changes on the remaining area are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2020 emissions data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models includes weather data from the PRISM Climate Group (PRISM Climate Group 2022). See Box 6-4 in the Methodology section of cropland remaining cropland for more information about the surrogate data method.

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land use patterns and irrigation histories are simulated with DayCent based on the 2017 USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. See the cropland remaining cropland section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in cropland remaining cropland. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data (see the Planned Improvements section in cropland remaining cropland).

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic carbon stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in grassland remaining grassland and Annex 3.12. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to grassland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) as described in the cropland remaining cropland section. Further elaboration on the methodology is also provided in Annex 3.12 for organic soils.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Annual carbon emissions from drained organic soils from 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to grassland and other land use conversions to woodlands are conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux in the forest land remaining forest land category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with a surrogate data method, which is also described in the Cropland Remaining Cropland section.

Uncertainty estimates are presented in Table 6-53 for each subsource (i.e., biomass carbon stocks, mineral and organic carbon stocks in soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total carbon stocks in land converted to grassland ranges from 156 percent below to 156 percent above the 2022 stock change estimate of 25.6 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is partly due to large uncertainties in biomass and dead organic matter carbon losses with forest land conversion to grassland, in addition to variation in soil organic carbon stock changes that is not explained by the surrogate data method.

Table 6-53: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Grassland (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(12.5)**	**(32.1)**	**7.0**	**-156%**	**156%**
Aboveground Live Biomass	(0.1)	(0.3)	+	-136%	134%
Belowground Live Biomass	+	+	+	-78%	100%
Dead Wood	+	(0.1)	+	-128%	100%
Litter	+	(0.1)	+	-170%	100%
Mineral Soil C Stocks: Tier 3	(11.6)	(31.0)	7.8	-167%	167%
Mineral Soil C Stocks: Tier 2	(1.7)	(3.7)	0.2	-114%	114%
Organic Soil C Stocks: Tier 2	1.0	+	2.0	-96%	96%
Forest Land Converted to Grassland	**46.8**	**12.2**	**81.4**	**-74%**	**74%**
Aboveground Live Biomass	31.8	(1.4)	64.9	-104%	104%
Belowground Live Biomass	4.4	(0.2)	9.0	-104%	105%
Dead Wood	2.4	(0.1)	5.0	-105%	104%
Litter	8.2	(0.4)	16.8	-104%	104%
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	+	-140%	140%
Organic Soil C Stocks: Tier 2	0.1	(0.0)	0.2	-130%	130%
Other Lands Converted to Grassland	**(8.0)**	**(12.9)**	**(3.1)**	**-61%**	**61%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-69%	44%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	(0.1)	+	-85%	100%
Litter	(0.1)	(0.1)	+	-60%	47%
Mineral Soil C Stocks: Tier 2	(7.9)	(12.8)	(3.0)	-62%	62%
Organic Soil C Stocks: Tier 2	0.1	+	0.1	-111%	111%
Settlements Converted to Grassland	**(0.8)**	**(1.0)**	**(0.5)**	**-35%**	**35%**
Aboveground Live Biomass	(0.2)	(0.3)	(0.1)	-56%	61%
Belowground Live Biomass	+	+	+	-42%	100%
Dead Wood	+	(0.1)	+	-67%	100%
Litter	(0.1)	(0.1)	+	-66%	59%
Mineral Soil C Stocks: Tier 2	(0.4)	(0.6)	(0.2)	-56%	56%
Organic Soil C Stocks: Tier 2	+	+	+	-432%	432%
Wetlands Converted to Grasslands	**0.1**	**(0.2)**	**0.3**	**-289%**	**283%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-85%	38%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	+	+	-95%	100%
Litter	+	+	+	-112%	100%
Mineral Soil C Stocks: Tier 2	+	+	+	-173%	173%
Organic Soil C Stocks: Tier 2	0.2	+	0.4	-112%	112%
Total: Land Converted to Grassland	**25.6**	**(14.4)**	**65.7**	**-156%**	**156%**
Aboveground Live Biomass	**31.3**	**(1.8)**	**64.5**	**-106%**	**106%**
Belowground Live Biomass	**4.3**	**(0.2)**	**9.0**	**-106%**	**106%**
Dead Wood	**2.3**	**(0.3)**	**4.8**	**-111%**	**111%**
Litter	**8.0**	**(0.6)**	**16.6**	**-107%**	**107%**
Mineral Soil C Stocks: Tier 3	**(11.6)**	**(31.0)**	**7.8**	**-167%**	**167%**
Mineral Soil C Stocks: Tier 2	**(10.1)**	**(15.4)**	**(4.9)**	**-52%**	**52%**

Organic Soil C Stocks: Tier 2	**1.4**	**0.4**	**2.4**	**-74%**	**74%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter carbon stock changes for conversions to agroforestry systems and herbaceous grasslands. The influence of agroforestry is difficult to address because there are currently no datasets to evaluate the trends in the area and associated carbon stocks in agroforestry systems. The influence of land use change to herbaceous grasslands and agroforestry will be further explored in a future *Inventory*.

QA/QC and Verification

See the QA/QC and Verification section in Cropland Remaining Cropland for information on QA/QC steps.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to grassland (see Recalculations Discussion of Chapter 6.2 Forest Land Remaining Forest Land for more details); c) constraining manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. Finally, see further updates in Section 6.2, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to grassland estimates. As a result, land converted to grassland has an estimated increase in losses of carbon stock changes, leading to a net change of 53 MMT CO_2 Eq. on average over the time series, representing a 237 percent change on average compared to the previous *Inventory*. Land converted to grassland is a net source of emissions across the time series based on the recalculations in this *Inventory*. This change from a net sink to a net source is mostly due to larger estimated losses of biomass and dead organic matter with forest land converted to grassland, and smaller estimated gains in mineral soil carbon stocks for cropland and other lands converted to grasslands.

Planned Improvements

The key improvement planned for the inventory is conducting an analysis of carbon stock changes for grassland in Alaska. This will resolve the majority of the discrepancy between the managed land base for land converted to grassland and amount of area currently included in land converted to grassland emissions and removals calculations (see Table 6-54).

Table 6-54: Comparison of Managed Land Area in Land Converted to Grassland and Area in the current Land Converted to Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	***Inventory***	**Difference**
1990	9,301	9,297	4
1991	9,492	9,488	4
1992	9,710	9,706	4
1993	11,619	11,615	4
1994	13,372	13,368	4
1995	14,039	14,035	4
1996	14,727	14,723	4

1997	15,411	15,408	4
1998	19,289	19,285	4
1999	20,143	20,139	4
2000	21,257	21,253	4
2001	22,349	22,345	4
2002	23,087	22,817	270
2003	22,986	22,445	541
2004	23,920	23,108	811
2005	24,091	23,009	1,082
2006	24,693	23,341	1,352
2007	24,694	23,072	1,622
2008	25,266	23,373	1,893
2009	25,424	23,260	2,163
2010	25,769	23,336	2,434
2011	26,176	23,471	2,704
2012	26,164	23,292	2,871
2013	25,154	22,116	3,038
2014	23,981	20,776	3,205
2015	24,101	20,730	3,372
2016	23,531	19,993	3,538
2017	22,808	19,270	3,538
2018	19,968	16,429	3,538
2019	19,546	16,008	3,538
2020	18,706	15,168	3,538
2021	17,351	*	*
2022	16,269	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

In addition, the amount of biomass carbon that is lost abruptly or the slower changes that continue to occur over a decade or longer with forest land converted to grasslands will be further refined in a future *Inventory*. The current values are estimated based on the amount of carbon before conversion and an estimated level of carbon left after conversion based on limited plot data from the FIA and published literature for the Western United States and Great Plains Regions. The amount of carbon left after conversion will be further investigated with additional data collection, particularly in the Western United States and Great Plains, including tree biomass, understory biomass, dead wood and litter carbon pools. In addition, biomass carbon stock changes will be estimated for conversions from other land uses to herbaceous grasslands. For information about other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

6.8 Wetlands Remaining Wetlands (CRT Category 4D1)

Wetlands remaining wetlands includes all wetlands in an inventory year that have been classified as a wetland for the previous 20 years, and in this *Inventory*, the flux estimates include peatlands, coastal wetlands, and flooded land.

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands that have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under peatlands remaining peatlands), and abandonment, restoration, rewetting, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely eliminated when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under the IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for peatlands remaining peatlands consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. Although methodologies are provided to estimate emissions and removals from rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines, information on the areal extent of rewetted/restored peatlands in the United States is currently unavailable. The current *Inventory* estimates CO_2, CH_4 and N_2O emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., peatlands remaining peatlands) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: *Sphagnum* bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from *Sphagnum* bogs in northern states, which is nutrient-poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient-rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from peatlands remaining peatlands using the Tier 1 approach. Current IPCC methodologies estimate only on-site N_2O and CH_4 emissions. This is because off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat where subsequent runoff or leaching into waterbodies can result in indirect N_2O emissions that are already included within the agricultural soil management category.

On-site emissions from managed peatlands occur as the land is drained and cleared of vegetation, and the underlying peat is exposed to sun, weather and oxygen. As this occurs, some of the peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands occurring on highly fertile/nutrient-rich soils, mostly located in the southern peatlands in Florida, contain significant amounts of organic nitrogen in inert/microbially inaccessible forms. Draining land in preparation for peat extraction allows bacteria to convert the organic nitrogen

into nitrates through nitrogen mineralization which leach to the surface where they are reduced to N_2O during nitrification. Nitrate availability also contributes to the activity of methanogens and methanotrophs that result in CH_4 emissions (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed to drain the land in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

Off-site CO_2 emissions from managed peatlands occur from waterborne dissolved organic carbon losses and the horticultural and landscaping use of peat. Dissolved organic carbon from water drained off peatlands reacts within aquatic ecosystems and is converted to CO_2, which is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). During the horticultural and landscaping use of peat, nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most (nearly 94 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for the aforementioned horticultural and landscaping purposes.

Total emissions from peatlands remaining peatlands are estimated to be 0.6 MMT CO_2 Eq. in 2022 (see Table 6-55 and Table 6-56) comprising 0.6 MMT CO_2 Eq. (572 kt) of CO_2, 0.004 MMT CO_2 Eq. (0.13 kt) of CH_4 and 0.0004 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2022 are 4.7 percent greater than total emissions in 2021.

Total emissions from peatlands remaining peatlands have fluctuated between 0.6 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993, followed by an increasing trend until reaching peak emissions in 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009. The trend reversed in 2009 and total emissions have generally decreased between 2009 and 2021, however, total emissions from peatlands increased slightly in 2022 compared to 2021. Carbon dioxide emissions from peatlands remaining peatlands have fluctuated between 0.6 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. Methane and N_2O emissions remained close to zero across the time series.

Table 6-55: Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.5**	**0.6**
Off-site	1.0	1.0	0.6	0.6	0.5	0.5	0.5
On-site	0.1	0.1	+	+	+	+	+
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Total	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-56: Emissions from Peatlands Remaining Peatlands (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1,055**	**1,101**	**650**	**613**	**590**	**547**	**572**
Off-site	985	1,030	608	572	550	509	533
On-site	70	71	42	41	41	38	39
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Off-Site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from peatlands remaining peatlands were calculated by apportioning the annual weight of peat produced in the United States (Table 6-57) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the conterminous 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS; USGS 1995 through 2018; USGS 2023a; USGS 2023b; USGS 2023c). Hawaii is assumed to have no peat production due to its absence from these sources. To develop these data, the USGS (U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The estimates for Alaska rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993 through 2015). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the *Alaska's Mineral Industry* report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the conterminous United States and Alaska, large variations in peat production can also result from variation in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates emissions from Alaska separately from the conterminous United States because Alaska previously conducted its own mineral surveys and reported peat production by volume, rather than by weight (Table 6-58). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[58] Peat production was not reported for 2015 in *Alaska's Mineral Industry 2014* report (DGGS 2015), and reliable data are not available beyond 2012, so Alaska's peat production in 2013 through 2021 (reported in cubic yards) was assumed to be equal to the 2012 value.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the On-Site CO_2 Emissions section below. Carbon dioxide emissions from dissolved organic carbon were estimated by multiplying the area of managed peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The United States has largely imported peat from Canada for horticultural purposes; in 2022, imports of *Sphagnum* moss (nutrient-poor) peat from Canada represented 96 percent of total U.S. peat imports and 80 percent of U.S. domestic consumption (USGS 2023c). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). To be consistent with the Tier 1 method, only domestic peat production is accounted for when estimating off-site emissions. Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

[58] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] *Sphagnum* moss are extensive" (USGS 2008).

Table 6-57: Peat Production of Conterminous 48 States (kt)

Type of Deposit	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	595.1	657.6	338.4	329.4	343.4	291.6	306.0
Nutrient-Poor	55.4	27.4	50.6	36.6	10.6	32.4	34.0
Total Production	**692.0**	**685.0**	**389.0**	**366.0**	**354.0**	**324.0**	**340.0**

Note: Totals may not sum due to independent rounding.

Sources: United States Geological Survey (USGS) (1991–2017) *Minerals Yearbook: Peat (1994–2016);* United States Geological Survey (USGS) (2018) *Minerals Yearbook: Peat – Tables-only release (2018);* United States Geological Survey (USGS) (2023) *Mineral Commodity Summaries: Peat (2023).*

Table 6-58: Peat Production of Alaska (Thousand Cubic Meters)

	1990	2005	2018	2019	2020	2021	2022
Total Production	49.7	47.8	93.1	93.1	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014)*.

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but consistent with IPCC (2006), an average production rate for the industry was applied to derive a land area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[59] The area of land managed for peat extraction in the conterminous United States was estimated using both nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year, see Table 6-59. The annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO_2 emission estimates.

Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from peatlands remaining peatlands in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the assumption that a single hectare yields 100 metric tons, see Table 6-60. The IPCC (2006) on-site emissions equation also includes a term that accounts for emissions resulting from the change in carbon stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in carbon stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

Table 6-59: Peat Production Area of Conterminous 48 States (Hectares)

	1990[a]	2005	2018	2019	2020	2021	2022
Nutrient-Rich	5,951	6,576	3,384	3,294	3,434	2,916	3,060
Nutrient-Poor	554	274	506	366	106	324	340
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**

[59] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

[a] A portion of the production in 1990 is of unknown nutrient type, resulting in a total production value greater than the sum of nutrient-rich and nutrient-poor.
Note: Totals may not sum due to independent rounding.

Table 6-60: Peat Production Area of Alaska (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	0	0	0	0	0	0	0
Nutrient-Poor	286	104	212	329	428	428	428
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

Note: Totals may not sum due to independent rounding.

On-site N_2O Emissions

IPCC (2006) indicates the calculation of on-site N_2O emission estimates using Tier 1 methodology only considers nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO_2 emissions methodology above details the calculation of nutrient-rich area data from production data. In order to estimate N_2O emissions, the land area estimate of nutrient-rich peatlands remaining peatlands was multiplied by the appropriate default emission factor taken from IPCC (2013). See the Planned Improvements section for additional information on identified research activities to improve peatland land area estimates.

On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the On-site CO_2 Emissions section above. In order to estimate CH_4 emissions from drained land surface, the land area estimate of peatlands remaining peatlands was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013). See Table 6-61 for the calculated area of ditches and drained land.

Table 6-61: Peat Production (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Conterminous 48 States							
Area of Drained Land	6,574	6,508	3,696	3,477	3,363	3,078	3,230
Area of Ditches	346	343	195	183	177	162	170
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**
Alaska							
Area of Drained Land	272	99	202	312	407	407	407
Area of Ditches	14	5	11	16	21	21	21
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. The same data sources were used throughout the time series, when available. When data were unavailable or the available data were outliers, missing values were estimated based on the past available data.

Uncertainty

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from peatlands remaining peatlands for 2022, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the conterminous United States, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).
- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.
- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-62. Carbon dioxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.5 and 0.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 16 percent below to 16 percent above the 2022 emission estimate of 0.6 MMT CO_2 Eq. Methane emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.001 and 0.006 MMT CO_2 Eq. This indicates a range of 59 percent below to 79 percent above the 2022 emission estimate of 0.004 MMT CO_2 Eq. Nitrous oxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.0002 and 0.0006 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 52 percent below to 53 percent above the 2022 emission estimate of 0.0004 MMT CO_2 Eq.

Table 6-62: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.6	0.5	0.7	-16%	+16%
Peatlands Remaining Peatlands	CH_4	+	+	+	-59%	+79%
Peatlands Remaining Peatlands	N_2O	+	+	+	-52%	+53%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

A QA/QC analysis was performed to review input data and calculations, and no issues were identified. In addition, the emission trends were analyzed to ensure they reflected activity data trends.

Recalculations Discussion

The conterminous United States peat production estimates for peatlands remaining peatlands were updated using the Peat section of the *Mineral Commodity Summaries 2023*. The 2023 edition updated 2018, 2019, 2020, and 2021 peat production data and provided peat type production estimates for 2022. Updated data decreased previously estimated emissions for 2018 by 18 percent, 2019 by 19 percent, 2020 by 19 percent, and 2021 by 22 percent versus estimated emissions for 2018, 2019, 2020, and 2021 in the previous (i.e., 1990 through 2021) *Inventory* for peatlands remaining peatlands. According to USGS, peat production estimations for 2018 through 2022 were revised in the *Mineral Commodity Summaries 2023* due to a company having shut down sometime in 2017 (USGS 2023d). Previously, USGS was estimating production for this company due to lack of peat production survey responses.

Although Alaska peat production data for 2015 through 2022 were unavailable, 2014 data are available in the *Alaska's Mineral Industry 2014* report. However, the reported values represented an apparent 98 percent decrease in production since 2012. Due to the uncertainty of the most recent data, 2013 through 2022 value were assumed to be equal to the 2012 value, seen in the *Alaska's Mineral Industry 2013* report. If updated Alaska data are available for the next *Inventory* cycle, this will result in a recalculation in the next (i.e., 1990 through 2023) *Inventory* report.

Planned Improvements

Edits to the trends and methodology sections are planned based on expert review comments.

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource:

- The implied emission factors will be calculated and included in this chapter for future *Inventories*. Currently, the N_2O emissions calculation uses different land areas than the CO_2 and CH_4 emission calculations (see Methodology and Time Series Consistency in this chapter), so estimating the implied emission factor per total land area is not appropriate. The inclusion of implied emission factors in this chapter will provide another method of QA/QC and verification for *Inventory* data.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement until data are available or identified:

- In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from peatlands remaining peatlands, future efforts will investigate if improved data sources exist for determining the quantity of peat harvested per hectare and the total area of land undergoing peat extraction.
- EPA plans to identify a new source for Alaska peat production. The current source has not been reliably updated since 2012 and Alaska Department of Natural Resources indicated future publication of data has been discontinued.

Coastal Wetlands Remaining Coastal Wetlands

Consistent with ecological definitions of wetlands,[60] the United States has historically included under the category of wetlands those coastal shallow water areas of estuaries and bays that lie within the extent of the Land Representation. Guidance on quantifying greenhouse gas emissions and removals on coastal wetlands is provided in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (*Wetlands Supplement*), which recognizes the particular importance of vascular plants in sequestering CO_2 from the atmosphere within biomass, dead organic material (DOM; including litter and dead wood stocks) and soils. Thus, the *Wetlands Supplement* provides specific guidance on quantifying emissions and removals on organic and

[60] See https://water.usgs.gov/nwsum/WSP2425/definitions.html; accessed August 2023.

mineral soils that are covered or saturated for part of the year by tidal fresh, brackish or saline water and are vegetated by vascular plants and may extend seaward to the maximum depth of vascular plant vegetation. The United States calculates emissions and removals based upon the stock change method for soil carbon (C) and the gain-loss method for biomass and DOM. Presently, this *Inventory* does not calculate the lateral flux of carbon to or from any land use. Lateral transfer of organic carbon to coastal wetlands and to marine sediments within U.S. waters is the subject of ongoing scientific investigation; there is currently no IPCC methodological guidance for lateral fluxes of carbon.

The United States recognizes both vegetated wetlands and unvegetated open water as coastal wetlands. Per guidance provided by the *Wetlands Supplement*, sequestration of carbon into biomass, DOM and soil carbon pools is recognized only in vegetated coastal wetlands and does not occur in unvegetated open water coastal wetlands. The United States takes the additional step of recognizing that carbon stock losses occur when vegetated coastal wetlands are converted to Unvegetated open water coastal wetlands.

This *Inventory* includes all privately- and publicly-owned coastal wetlands (i.e., mangroves and tidal marsh) along the oceanic shores of the conterminous United States, including the District of Columbia., but does not include coastal wetlands remaining coastal wetlands in Alaska, Hawaii, or any of the United States Territories. Seagrasses are not currently included within the *Inventory* due to insufficient data on distribution, change through time and carbon stocks or carbon stock changes as a result of anthropogenic influence (see Planned Improvements).

Under the coastal wetlands remaining coastal wetlands category, the following emissions and removals are quantified in this chapter:

1) Carbon stock changes and CH_4 emissions on vegetated coastal wetlands remaining vegetated coastal wetlands,

2) Carbon stock changes on vegetated coastal wetlands converted to unvegetated open water coastal wetlands,

3) Carbon stock changes on unvegetated open water coastal wetlands converted to vegetated coastal wetlands, and

4) Nitrous oxide emissions from aquaculture in coastal wetlands.

Vegetated coastal wetlands hold carbon in all five carbon pools (i.e., aboveground biomass, belowground biomass, dead organic matter [DOM; dead wood and litter], and soil), though typically soil carbon and, to a lesser extent, aboveground and belowground biomass are the dominant pools, depending on wetland type (i.e., forested vs. marsh). vegetated coastal wetlands are net accumulators of carbon over centuries to millennia as soils accumulate carbon under anaerobic soil conditions and carbon accumulates in plant biomass. Large emissions from soil carbon and biomass stocks occur when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands (e.g., when vegetated coastal wetlands are lost due to subsidence, channel cutting through vegetated coastal wetlands), but are still recognized as coastal wetlands in this *Inventory*. These carbon stock losses resulting from conversion to unvegetated open water coastal wetlands can cause the release of decades to centuries of accumulated soil carbon, as well as the standing stock of biomass carbon. Conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands, either through restoration efforts or naturally, initiates the building of carbon stocks within soils and biomass. In applying the *Wetlands Supplement* methodologies for estimating CH_4 emissions, coastal wetlands in salinity conditions greater than 18 parts per thousand have little to no CH_4 emissions compared to those experiencing lower salinity brackish and freshwater conditions. Therefore, conversion of vegetated coastal wetlands to or from unvegetated open water coastal wetlands are conservatively assumed to not result in a change in salinity condition and are assumed to have no impact on CH_4 emissions. The *Wetlands Supplement* provides methodologies to estimate N_2O emissions from coastal wetlands that occur due to aquaculture. The N_2O emissions from aquaculture result from the nitrogen derived from consumption of the applied food stock that is then excreted as nitrogen load available for conversion to N_2O. While N_2O emissions can also occur due to anthropogenic nitrogen loading from the watershed and atmospheric deposition, these

emissions are not reported here to avoid double-counting of indirect N_2O emissions with the agricultural soils management, forest land and settlements categories.

The *Wetlands Supplement* provides methodologies for estimating carbon stock changes and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, carbon stock changes from mangroves may be reported under the forest land category or under coastal wetlands. If mangrove stature is 5 m or greater or if there is evidence that trees can obtain that height, mangroves are reported under the forest land category because they meet the definition of forest land. Mangrove forests that are less than 5 m are reported under coastal wetlands because they meet the definition of wetlands. All other non-drained, intact coastal marshes are reported under coastal wetlands.

Because of human activities and level of regulatory oversight, all coastal wetlands within the conterminous United States are included within the managed land area described in Section 6.1, and as such, estimates of carbon stock changes, emissions of CH_4, and emissions of N_2O from aquaculture from all coastal wetlands are included in this *Inventory.* At the present stage of inventory development, coastal wetlands are not explicitly shown in the land representation analysis while work continues to harmonize data from NOAA's Coastal Change Analysis Program (C-CAP)[61] with NRI, FIA and NLDC data used to compile the land representation (see Section 6.1). However, a check was undertaken to confirm that coastal wetlands recognized by C-CAP represented a subset of wetlands recognized by the NRI for marine coastal states.

The greenhouse gas fluxes for all four wetland categories described above are summarized in Table 6-63. Coastal wetlands remaining coastal wetlands are generally a net carbon sink, with the fluxes ranging from -5.6 to -6.7 MMT CO_2 Eq. across the majority of the time series; however, between 2006 and 2010, they were a net source of emissions (ranging from 3.2 to 53.5 MMT CO_2 Eq.), resulting from a large loss of vegetated coastal wetlands to open water due to hurricanes (Table 6-63). Recognizing removals of CO_2 to soil of 12.5 MMT CO_2 Eq. and CH_4 emissions of 4.3 MMT CO_2 Eq. in 2022, vegetated coastal wetlands remaining vegetated coastal wetlands are a net sink of 8.2MMT CO_2 Eq. Loss of coastal wetlands, primarily in the Mississippi Delta as a result of hurricane impacts and sediment diversion and other human impacts, recognized as vegetated coastal wetlands converted to unvegetated coastal wetlands, drive an emission of 1.5 MMT CO_2 Eq. since 2011, primarily from soils. Building of new wetlands from open water, recognized as unvegetated coastal wetlands converted to vegetated coastal, results each year in removal of 0.1 MMT CO_2 Eq. Aquaculture is a minor industry in the United States, resulting in an emission of N_2O across the time series of between 0.1 to 0.2 MMT CO_2 Eq. In total, coastal wetlands are a net sink of 6.7 MMT CO_2 Eq. in 2022.

Table 6-63: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(8.4)**	**(8.4)**	**(8.3)**	**(8.3)**	**(8.3)**	**(8.2)**	**(8.2)**
Biomass C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Net CH_4 Flux	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Biomass C Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter C Flux	+	+	+	+	+	+	+
Soil C Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Unvegetated Open Water Coastal Wetlands Converted to Vegetated	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

[61] See https://coast.noaa.gov/digitalcoast/tools/lca.html; accessed September 2023.

Coastal Wetlands							
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	+	+	+	+	+
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Net N_2O Flux from Aquaculture in Coastal Wetlands	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Biomass C Flux	**+**	**+**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Total Dead Organic Matter C Flux	**(+)**	**(+)**	**+**	**+**	**+**	**+**	**+**
Total Soil C Flux	**(10.8)**	**(10.1)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.1)**
Total CH_4 Flux	**4.2**	**4.2**	**4.3**	**4.3**	**4.3**	**4.3**	**4.3**
Total N_2O Flux	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Flux	**(6.5)**	**(5.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions and Removals from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands

The conterminous United States currently has 2.98 million hectares of intertidal vegetated coastal wetlands remaining vegetated coastal wetlands comprised of tidally influenced palustrine emergent marsh (663,014 ha), palustrine scrub shrub (133,582 ha) and estuarine emergent marsh (1,892,507 ha), estuarine scrub shrub (95,225 ha) and estuarine forested wetlands (195,199 ha). Mangroves fall under both estuarine forest and estuarine scrub shrub categories depending upon height. Dwarf mangroves, found in subtropical states along the Gulf of Mexico, do not attain the height status to be recognized as forest land, and are therefore always classified within vegetated coastal wetlands. vegetated coastal wetlands remaining vegetated coastal wetlands are found in cold temperate (53,968 ha), warm temperate (896,583 ha), subtropical (1,966,101 ha) and Mediterranean (62,874 ha) climate zones.

Soils are the largest carbon pool in vegetated coastal wetlands remaining vegetated coastal wetlands, reflecting long-term removal of atmospheric CO_2 by vegetation and transfer into the soil pool in the form of both autochthonous and allochthonous decaying organic matter. Soil carbon emissions are not assumed to occur in coastal wetlands that remain vegetated. This *Inventory* includes changes in carbon stocks in both biomass and soils. Changes in DOM carbon stocks are not included. Methane emissions from decomposition of organic matter in anaerobic conditions are present at salinity less than half that of sea water. Mineral and organic soils are not differentiated in terms of carbon stock changes or CH_4 emissions.

Table 6-64 through Table 6-66 summarize nationally aggregated biomass and soil carbon stock changes and CH_4 emissions on vegetated coastal wetlands remaining vegetated coastal wetlands. Intact vegetated coastal wetlands remaining vegetated coastal wetlands hold a total biomass carbon stock of 35.96 MMT C. Removals from biomass carbon stocks in 2022 were 0.05 MMT CO_2 Eq. (0.01 MMT C), which has increased over the time series (Table 6-64 and Table 6-65). Carbon dioxide emissions from biomass in vegetated coastal wetlands remaining vegetated coastal wetlands between 2002 and 2011, with very low sequestration between 2002 and 2006 and emissions of 0.21 MMT CO_2 Eq. between 2007 and 2011, are not inherently typical and are a result of coastal wetland loss over time. Most of the coastal wetland loss has occurred in palustrine and estuarine emergent wetlands. Vegetated coastal wetlands maintain a large carbon stock within the top 1 meter of soil (estimated to be 804 MMT C) to which carbon accumulated at a rate of 12.5 MMT CO_2 Eq. (3.4 MMT C) in 2022, a value that has remained relatively constant across the reporting period. For vegetated coastal wetlands remaining vegetated coastal wetlands, methane emissions of 4.3 of MMT CO_2 Eq. (154 kt CH_4) in 2022 (Table 6-66) offset carbon removals resulting in a net removal of 8.2 MMT CO_2 Eq. in 2022; this rate has been relatively consistent across the reporting period. Dead organic matter stock changes are not calculated in vegetated coastal wetlands remaining vegetated coastal wetlands since this stock is considered to be in a steady state when using Tier 1 methods (IPCC 2014). Due to federal regulatory protection, loss of vegetated coastal wetlands through human activities slowed considerably

in the 1970s and the current annual rates of carbon stock change and CH_4 emissions are relatively constant over time.

Table 6-64: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Total C Stock Change	**(12.6)**	**(12.6)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**

+ Absolute value does not exceed 0.05 MMT $C0_2$ Eq.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-65: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	+	(+)	(+)	(+)	(+)	(+)
Soil Flux	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)	(3.4)
Total C Stock Change	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4)**

+ Absolute value does not exceed 0.05 MMT C.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-66: CH_4 Emissions from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Year	1990	2005	2018	2019	2020	2021	2022
Methane Emissions (MMT CO_2 Eq.)	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Methane Emissions (kt CH_4)	149	151	153	153	154	154	154

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in biomass carbon stocks, soil carbon stocks and emissions of CH_4 for vegetated coastal wetlands remaining vegetated coastal wetlands. Dead organic matter is not calculated for vegetated coastal wetlands remaining vegetated coastal wetlands since it is assumed to be in steady state (IPCC 2014).

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Above- and belowground biomass carbon stocks for palustrine (freshwater) and estuarine (saline) marshes are estimated for vegetated coastal wetlands remaining vegetated coastal wetlands on land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2022 from these datasets. Based upon NOAA C-CAP, coastal wetlands are subdivided into palustrine and estuarine classes and further subdivided into emergent marsh, scrub shrub and forest classes (Table 6-67). Biomass is not sensitive to soil organic matter content but is differentiated based on climate zone. Aboveground biomass carbon stocks for non-forested wetlands data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground

biomass carbon stock for subtropical estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017). Root to shoot ratios from the *Wetlands Supplement* (Table 6-69; IPCC 2014) were used to account for belowground biomass, which were multiplied by the aboveground carbon stock. Above- and belowground values were summed to obtain total biomass carbon stocks. Biomass carbon stock changes per year for wetlands remaining wetlands were determined by calculating the difference in area between that year and the previous year to calculate gain/loss of area for each climate type, which was multiplied by the mean biomass for that climate type.

Table 6-67: Area of Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands, Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands, and Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (ha)

Year	1990	2005	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,975,477	2,985,783	2,974,523	2,975,789	2,977,055	2,978,322	2,979 588
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	1,720	2,515	1,488	1,488	1,488	1,488	1,488
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	952	1,769	2,406	2,406	2,406	2,406	2,406

Table 6-68: Aboveground Biomass Carbon Stocks for Vegetated Coastal Wetlands (t C ha^{-1})

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	3.25	3.17	2.24	4.69
Palustrine Emergent Wetland	3.25	3.17	2.24	4.69
Estuarine Forested Wetland	N/A	N/A	17.83	N/A
Estuarine Scrub/Shrub Wetland	3.05	3.05	2.43	3.44
Estuarine Emergent Wetland	3.05	3.10	2.43	3.44

Source: All data from Byrd et al. (2017, 2018 and 2020) except for subtropical estuarine forested wetlands, which is from Lu and Megonigal (2017); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Table 6-69: Root to Shoot Ratios for Vegetated Coastal Wetlands

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.15	1.15	3.65	3.63
Palustrine Emergent Wetland	1.15	1.15	3.65	3.63
Estuarine Forested Wetland	N/A	N/A	0.96	N/A
Estuarine Scrub/Shrub Wetland	2.11	2.11	3.65	3.63
Estuarine Emergent Wetland	2.11	2.11	3.65	3.63

Source: All values from IPCC (2014); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands remaining vegetated coastal wetlands for both mineral and organic soils. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Table 6-70; Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al.

2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012a&b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022).

Tier 2 estimates of soil carbon removals associated with annual soil carbon accumulation on managed vegetated coastal wetlands remaining vegetated coastal wetlands were developed with country-specific soil carbon removal factors multiplied by activity data of land area for vegetated coastal wetlands remaining vegetated coastal wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of vegetated coastal wetlands remaining vegetated coastal wetlands on an annual basis. To estimate soil carbon stock changes, no differentiation is made between organic and mineral soils since currently, no statistical evidence supports disaggregation (Holmquist et al. 2018).

Table 6-70: Annual Soil Carbon Accumulation Rates for Vegetated Coastal Wetlands (t C ha^{-1} yr^{-1})

Climate Zone	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.010	1.544	0.45	0.845
Palustrine Emergent Wetland	1.010	1.544	0.454	0.845
Estuarine Forested Wetland	N/A	N/A	0.821	N/A
Estuarine Scrub/Shrub Wetland	1.254	1.039	0.821	0.845
Estuarine Emergent Wetland	1.254	1.039	1.587	0.845

Source: All data from CCRCN (2023)[62]; N/A means there are no estuarine forested wetlands outside of subtropical regions.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for vegetated coastal wetlands remaining vegetated coastal wetlands are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *Wetlands Supplement.* The methodology follows Equation 4.9, Chapter 4 of the *Wetlands Supplement*; Tier 1 emissions factors are multiplied by the area of freshwater (palustrine) coastal wetlands. The CH_4 fluxes applied are determined based on salinity; only palustrine wetlands are assumed to emit CH_4. Estuarine coastal wetlands in the C-CAP classification include wetlands with salinity less than 18 ppt, a threshold at which methanogenesis begins to occur (Poffenbarger et al. 2011), but the dataset currently does not differentiate estuarine wetlands based on their salinities and, as a result, CH_4 emissions from estuarine wetlands are not included at this time.

Uncertainty

Underlying uncertainties in the estimates of soil and biomass carbon stock changes and CH_4 emissions include uncertainties associated with Tier 2 literature values of soil carbon stocks, biomass carbon stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to vegetated coastal wetlands remaining vegetated coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil carbon stock and CH_4 flux applied. Uncertainties for soil and biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Because mean soil and biomass carbon stocks for each available community

[62] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed September 2023.

class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *2013 Wetlands Supplement*. Uncertainties for CH_4 flux are the Tier 1 default values reported in the *2013 IPCC Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to apply CH_4 flux emission factors (delineation of an 18 ppt boundary) that will need significant improvement to reduce uncertainties. Details on the emission/removal trends and methodologies through time are described in more detail in the introduction and the Methodology section. The combined uncertainty was calculated using the IPCC Approach 1 method of summing the squared uncertainty for each individual source (C-CAP, soil, biomass and CH_4) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-71 for each subcategory (i.e., soil carbon, biomass carbon and CH_4 emissions). The combined uncertainty across all subcategory is 37.0 percent below and above the estimate of -6.4 MMT CO_2 Eq, which is primarily driven by the uncertainty in the CH_4 estimates because there is high variability in CH_4 emissions when the salinity is less than 18 ppt. In 2021, the total flux was -8.2 MMT CO_2 Eq., with lower and upper estimates of -11.3 and -5.2 MMT CO_2 Eq.

Table 6-71: IPCC Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes and CH_4 Emissions occurring within Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands in 2021 (MMT CO_2 Eq. and Percent)

Source/Sink	Gas	2022 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Change	CO_2	(0.05)	(0.06)	(0.03)	-24.1%	+24.1%
Soil C Stock Change	CO_2	(12.5)	(14.7)	(10.3)	-17.7	+17.7%
CH_4 emissions	CH_4	4.3	3.0	5.6	-29.9%	+29.9%
Total Flux		**(8.2)**	**(11.3)**	**(5.2)**	**-36.5%**	**+36.5%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided the National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal QA/QC assessment consistent with the general QC checks outlined in the Inventory QA/QC Plan. Acceptance of final datasets into archive and dissemination are contingent upon the product compilation being compliant with mandatory QA/QC requirements (McCombs et al. 2016). QA/QC and verification of soil carbon stock datasets have been provided by the Smithsonian Environmental Research Center and coastal wetland inventory team leads who reviewed summary tables against reviewed sources. Biomass carbon stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads before inclusion in this *Inventory*. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil and biomass carbon stock change data are based upon peer-reviewed literature and CH_4 emission factors derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub

wetlands, which resulted in an annual average increase of removals of 2.3 MMT CO_2 Eq. for the entire time series. For vegetated coastal wetlands remaining vegetated coastal wetlands in 2022, inclusion of the updated values resulted in an increase of the sink from -5.9 MMT CO_2 Eq. to -8.2 MMT CO_2 Eq.

Planned Improvements

Harmonization across all spatial datasets used to calculate activity data is underway. Once completed, a better representation of forested tidal wetlands, palustrine tidal wetlands, and forest land near the tidal boundary will be obtained.

Work is currently underway to examine the feasibility of incorporating seagrass soil and biomass carbon stocks into the vegetated coastal wetlands remaining vegetated coastal wetlands estimates. Additionally, investigation into quantifying the distribution, area, and emissions resulting from impounded waters (i.e., coastal wetlands where tidal connection to the ocean has been restricted or eliminated completely) is underway.

Box 6-6: State-Level Case Studies for the Estimation of GHG Removals in Seagrasses

North Carolina and Maryland are the first states to include seagrasses within their state-level inventory. North Carolina has the largest extent of seagrass coverage along the U.S. Atlantic coast, measuring approximately 86,412 acres in 2021. Seagrass mapping efforts occurred in 2007, 2013, and 2020 using a field-validated aerial image classification. The Tier 1 soil carbon accumulation rate was used and currently, biomass is not included due to lack of local data. The analysis shows that these high salinity seagrass habitats provided a net carbon sink to the state, although greenhouse gas removals decreased over time due to loss in seagrass coverage. Overall, seagrass beds in 2021 sequestered approximately 0.055 MMT CO_2 Eq. (55.14 kt CO_2 Eq.) in the soils alone.

In Maryland, the state greenhouse gas inventory comprises blue carbon stocks and fluxes from estuarine wetlands and seagrasses. Maryland currently has long-term monitoring of submerged aquatic vegetation (SAV) extent and density through annual surveying, and the rate of carbon sequestration and methane emission was a regional average for coastal wetlands. This study at state-level calculation offers an opportunity to maintain consistency in reporting across spatial scales and allows positioning SAV in its role as a carbon sink, in addition to its benefits in water quality and habitat conservation, perpetuating Maryland's role as a leader in blue carbon accounting.

These two case studies demonstrate the importance of refining emission factor data and harmonizing the inclusion of this ecosystem in the land representation analysis (reconciling the National Ocean and Atmospheric Administration [NOAA] Coastal Change Analysis Program [C-CAP] data with the National Resource Inventory, Forest Inventory Analysis, and the National Land Cover Database).

Emissions from Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands

Vegetated coastal wetlands converted to unvegetated open water coastal wetlands is a source of emissions from soil, biomass, and DOM carbon stocks. An estimated 1,488 ha of vegetated coastal wetlands were converted to unvegetated open water coastal wetlands in 2022, which largely occurred within estuarine and palustrine emergent wetlands. Prior to 2006, annual conversion to unvegetated open water coastal wetlands was higher than current rates: 1,720 between 1990 and 2000 and 2,515 ha between 2001 and 2005. The Mississippi Delta represents more than 40 percent of the total coastal wetland of the United States, and over 90 percent of the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands. The drivers of coastal wetlands loss include legacy human impacts on sediment supply through rerouting river flow, direct impacts of channel cutting on hydrology, salinity and sediment delivery, and accelerated subsidence from aquifer extraction.

Each of these drivers directly contributes to wetland erosion and subsidence, while also reducing the resilience of the wetland to build with sea-level rise or recover from hurricane disturbance. Over recent decades, the rate of Mississippi Delta wetland loss has slowed, though episodic mobilization of sediment occurs during hurricane events (Couvillion et al. 2011; Couvillion et al. 2016). The land cover analysis between the 2006 and 2011 C-CAP surveys coincides with two such events, hurricanes Katrina and Rita (both making landfall in the late summer of 2005), that occurred between these C-CAP survey dates. The subsequent 2016 C-CAP survey determined that erosion rates had slowed.

Shallow nearshore open water within the U.S. land representation is recognized as falling under the coastal wetlands category within this *Inventory*. While high resolution mapping of coastal wetlands provides data to support IPCC Approach 2 methods for tracking land cover change, the depth in the soil profile to which sediment is lost is less clear. This *Inventory* adopts the Tier 1 methodological guidance from the *Wetlands Supplement* for estimating emissions following the methodology for excavation (see Methodology section, below) when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with estimates of wetland carbon loss provided in the literature and the *Wetlands Supplement* (Crooks et al. 2009; Couvillion et al. 2011; Delaune and White 2012; IPCC 2014). The same assumption on depth of soils impacted by erosion has been applied here. It is a reasonable Tier 1 assumption, based on experience, but estimates of emissions are sensitive to the depth to which the assumed disturbances have occurred (Holmquist et al. 2018). A Tier 1 assumption is also adopted in that all mobilized carbon is immediately returned to the atmosphere (as assumed for terrestrial land-use categories), rather than redeposited in long-term carbon storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland carbon based upon the geomorphic setting of the depositional environment.

In 2022, there were 1,488 ha of vegetated coastal wetlands converted to unvegetated open water coastal wetlands (Table 6-67) across all wetland types and climates, which resulted in 1.5 MMT CO_2 Eq. (0.4 MMT C) and 0.06 MMT CO_2 Eq. (0.02 MMT C) lost through soil and biomass, respectively, with minimal DOM C stock loss (Table 6-72, and Table 6-73). Across the reporting period, the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands was greatest between the 2006 to 2011 C-CAP reporting period (11,373 ha) and has decreased since then to current levels (Table 6-67).

Table 6-72: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Total C Stock Change	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-73: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	+	+	+	+	+	+	+
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	0.5	0.7	0.4	0.4	0.4	0.4	0.4
Total C Stock Change	**0.5**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

+ Absolute value does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM carbon stocks for vegetated coastal wetlands converted to unvegetated open water coastal wetlands.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Biomass carbon stock changes for palustrine and estuarine marshes are estimated for vegetated coastal wetlands converted to unvegetated open water coastal wetlands on lands below the elevation of high tides (taken to be mean high water spring tide elevation) within the U.S. land representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Publicly-owned and privately-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2021 from these datasets. The C-CAP database provides peer reviewed country-specific mapping to support IPCC Approach 3 quantification of coastal wetland distribution, including conversion to and from open water. Biomass carbon stocks are not sensitive to soil organic content but are differentiated based on climate zone. Non-forested aboveground biomass carbon stock data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[63]; Table 6-68). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-69; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks. Conversion to open water results in emissions of all biomass carbon stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year in each climate zone by its mean biomass.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks for subtropical estuarine forested wetlands, are an emission from vegetated coastal wetlands converted to unvegetated open water coastal wetlands across all years in the time series. Data on DOM carbon stocks are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2021 time series. Conversion to open water results in emissions of all DOM carbon stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year by its Tier 1 DOM carbon stock.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands converted to unvegetated open water coastal wetlands. Country-specific soil carbon stocks were updated in 2018 based upon analysis of an assembled dataset of 1,959 cores from across the conterminous United States (Holmquist et al. 2018). This analysis

[63] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed September 2023.

demonstrated that it was not justified to stratify carbon stocks based upon mineral or organic soil classification, climate zone, or wetland classes; therefore, a single soil carbon stock of 270 t C ha^{-1} was applied to all classes. Following the Tier 1 approach for estimating CO_2 emissions with extraction provided within the *Wetlands Supplement*, soil carbon loss with conversion of vegetated coastal wetlands to unvegetated open water coastal wetlands is assumed to affect soil carbon stock to one-meter depth (Holmquist et al. 2018) with all emissions occurring in the year of wetland conversion, and multiplied by activity data of vegetated coastal wetland area converted to unvegetated open water wetlands. The methodology follows Eq. 4.6 in the *Wetlands Supplement*.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of vegetated coastal wetlands to unvegetated open water coastal wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass carbon stock changes are associated with country-specific (Tier 2) literature values of these stocks, while the uncertainties with the Tier 1 estimates are associated with subtropical estuarine forested wetland DOM stocks. Assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data are also included in this uncertainty assessment. The IPCC default assumption of 1 m of soil erosion with anthropogenic activities was adopted to provide standardization in U.S. tidal carbon accounting (Holmquist et al. 2018). This depth of potentially erodible tidal wetland soil has not been comprehensively addressed since most soil cores analyzed were shallow (e.g., less than 50 cm) and do not necessarily reflect the depth to non-wetland soil or bedrock (Holmquist et al. 2018). Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil carbon stock applied. Because mean soil and biomass carbon stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon stocks, the mean standard error was very low and largely influenced by the uncertainty associated with the estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks was derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (+/-10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-74 for each subcategory (i.e., soil carbon, biomass carbon, and DOM emissions). The combined uncertainty across all subcategory is 32.0 percent above and below the estimate of 1.5 MMT CO_2 Eq, which is driven by the uncertainty in the soil carbon estimates. In 2022, the total carbon flux was 1.5 MMT CO_2 Eq., with lower and upper estimates of 1.0 and 2.0 MMT CO_2 Eq.

Table 6-74: Approach 1 Quantitative Uncertainty Estimates for CO_2 Flux Occurring within Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock	0.06	0.05	0.08	-24.1%	+24.1%
Dead Organic Matter C Stock	0.0005	0.000	0.001	-25.8%	+25.8%
Soil C Stock	1.5	1.3	1.7	-15.0%	+15.0%
Total Flux	**1.5**	**1.0**	**2.0**	**-32.0%**	**+32.0%**

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

Data provided by NOAA (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC procedures. Acceptance of final datasets into archive and dissemination are contingent upon assurance that the data product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of the soil carbon stock dataset have been provided by the Smithsonian Environmental Research Center and by the Coastal Wetlands project team leads who reviewed the estimates against primary scientific literature. Biomass carbon stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads before inclusion in the *Inventory*. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and were verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

The depth of soil carbon affected by conversion of vegetated coastal wetlands converted to unvegetated coastal wetlands will be updated from the IPCC default assumption of 1 m of soil erosion when mapping and modeling advancements can quantitatively improve accuracy and precision. Improvements are underway to address this, first conducting a review of literature publications. Until the time where these more detailed and spatially distributed data are available, the IPCC default assumption that the top 1 m of soil is disturbed by anthropogenic activity will be applied. This is a longer-term improvement.

More detailed research is in development that provides a longer-term assessment and more highly refined rates of wetlands loss across the Mississippi Delta (e.g., Couvillion et al. 2016). The Mississippi Delta is the largest extent of coastal wetlands in the United States. Higher resolution imagery analysis would improve quantification of conversation to open water, which occurs not only at the edge of the marsh but also within the interior. Improved mapping could provide a more refined regional Approach 2-3 land representation to support the national-scale assessment provided by C-CAP.

An approach for calculating the fraction of remobilized coastal wetland soil carbon returned to the atmosphere as CO_2 is currently under review and may be included in future reports.

Research by USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands is also underway. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the *Inventory*.

Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands

Open water within the U.S. land base, as described in Section 6.1, is recognized as coastal wetlands within this *Inventory*. The appearance of vegetated tidal wetlands on lands previously recognized as open water reflects either the building of new vegetated marsh through sediment accumulation or the transition from other lands uses through an intermediary open water stage as flooding intolerant plants are displaced and then replaced by wetland plants. Biomass, DOM and soil carbon accumulation on unvegetated open water coastal wetlands converted to vegetated coastal wetlands begins with vegetation establishment.

Within the United States, conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands is predominantly due to engineered activities, which include active restoration of wetlands (e.g., wetlands restoration in San Francisco Bay), dam removals or other means to reconnect sediment supply to the nearshore (e.g., Atchafalaya Delta, Louisiana, Couvillion et al. 2011). Wetland restoration projects have been ongoing in the United States since the 1970s. Early projects were small, a few hectares in size. By the 1990s, restoration projects, each hundreds of hectares in size, were becoming common in major estuaries. In several coastal areas e.g., San Francisco Bay, Puget Sound, Mississippi Delta and south Florida, restoration activities are in planning and implementation phases, each with the goal of recovering tens of thousands of hectares of wetlands.

In 2022, 2,406 ha of unvegetated open water coastal wetlands were converted to vegetated coastal wetlands across all wetland types and climates, which has steadily increased over the reporting period (Table 6-66). This resulted in 0.007 MMT CO_2 Eq. (0.002 MMT C) and 0.1 MMT CO_2 Eq. (0.03 MMT C) sequestered in soil and biomass, respectively (Table 6-75 and Table 6-76). The soil carbon stock has increased during the *Inventory* reporting period, likely due to increasing vegetated coastal wetland restoration over time. While DOM carbon stock increases are present, they are minimal in the early part of the time series and zero in the later because there are no conversions from unvegetated open water coastal wetlands to subtropical estuarine forested wetlands between 2011 and 2016 (and by proxy through 2022), and that is the only coastal wetland type where DOM data is currently available.

Throughout the reporting period, the amount of open water coastal wetlands converted to vegetated coastal wetlands has increased over time, reflecting the increase in engineered restoration activities mentioned above.

Table 6-75: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-76: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass C Flux	(0.01)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(0.01)**	**(0.02)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**

+ Absolute value does not exceed 0.005 MMT C.

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM carbon stocks, and CH_4 emissions for unvegetated open water coastal wetlands converted to vegetated coastal wetlands.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Quantification of regional coastal wetland biomass carbon stock changes for palustrine and estuarine marsh vegetation are presented for unvegetated open water coastal wetlands converted to vegetated coastal wetlands on lands below the elevation of high tides (taken to be mean high water spring tide elevation) according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Privately-owned and publicly-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2022 from these datasets (Table 6-65). C-CAP provides peer reviewed high resolution level mapping of coastal wetland distribution, including conversion to and from open water. Biomass carbon stock is not sensitive to soil organic content but differentiated based on climate zone. Data for non-forested wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Table 6-68; Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for subtropical estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[64]). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-69; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks.

Conversion of open water to vegetated coastal wetlands results in the establishment of a standing biomass carbon stock; therefore, stock changes that occur are calculated by multiplying the C-CAP derived area gained that year in each climate zone by its mean biomass. While the process of revegetation of unvegetated open water wetlands can take many years to occur, it is assumed in the calculations that the total biomass is reached in the year of conversion.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are included for subtropical estuarine forested wetlands for vegetated coastal wetlands converted to unvegetated open water coastal wetlands across all years. Tier 1 default or country-specific data on DOM are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. Tier 1 estimates of subtropical estuarine forested wetland DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2021 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by its Tier 1 DOM C stock. Similar to biomass carbon stock gains, gains in DOM can take many years to occur, but for this analysis, the total DOM stock is assumed to accumulate during the first year of conversion.

Soil Carbon Stock Change

Soil carbon stock changes are estimated for unvegetated open water coastal wetlands converted to vegetated coastal wetlands. Country-specific soil carbon removal factors associated with soil carbon accretion, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature and updated this year based upon refined review of the dataset (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al.

[64] See https://doi.org/10.25573/serc.21565671; accessed September 2023.

2013; Drexler et al. 2013; Watson and Byrne 2013; Crooks et al. 2014; Breithaupt et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). Soil carbon stock changes are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil carbon stock change, no differentiation is made for soil type (i.e., mineral, organic). Soil carbon removal factors were developed from literature references that provided soil carbon removal factors disaggregated by climate region and vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above (see Table 6-70 for values).

Tier 2 level estimates of carbon stock changes associated with annual soil carbon accumulation in vegetated coastal wetlands were developed using country-specific soil carbon removal factors multiplied by activity data on unvegetated coastal wetlands converted to vegetated coastal wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of unvegetated coastal wetlands converted to vegetated coastal wetlands on an annual basis.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of vegetated open water coastal wetlands to vegetated coastal wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass carbon stock changes include uncertainties associated with country-specific (Tier 2) literature values of these carbon stocks, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes that determines the soil carbon stock applied. Because mean soil and biomass carbon stocks for each available community class are in a fairly narrow range, the same overall uncertainty was applied to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon stocks, the mean standard error was very low and largely influenced by error in estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass (Table 6-69), are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks were derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-77 for each subcategory (i.e., soil carbon, biomass carbon and DOM emissions). The combined uncertainty across all subsources is 33.43 percent above and below the estimate of -0.1 MMT CO_2 Eq. In 2022, the total carbon flux was -0.1 MMT CO_2 Eq., with lower and upper estimates of -0.1 and -0.08 MMT CO_2 Eq.

Table 6-77: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring within Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range (MMT CO_2 Eq.)		Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	(0.1)	(0.12)	(0.08)	-20.0%	+20.0%
Dead Organic Matter C Stock Flux	0	0	0	-25.8%	+25.8%
Soil C Stock Flux	(0.008)	(0.009)	(0.006)	-17.7%	+17.7%
Total Flux	**(0.1)**	**(0.14)**	**(0.01)**	**-33.3%**	**+33.3%**

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided data (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping), which undergo internal agency QA/QC assessment procedures. Acceptance of final datasets into the archive for dissemination are contingent upon assurance that the product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of soil carbon stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetlands project team leads who reviewed the summary tables against primary scientific literature. Aboveground biomass carbon reference stocks are derived from an analysis by the Blue Carbon Monitoring project and reviewed by U.S. Geological Survey prior to publishing, the peer-review process during publishing, and the coastal wetland inventory team leads before inclusion in the *Inventory*. Root to shoot ratios and DOM data are derived from peer-reviewed literature and undergo review as per IPCC methodology. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed and verified by a second QA team. A team of two evaluated and verified there were no computational errors within calculation worksheets. Two biogeochemists at the USGS, also members of the NASA Carbon Monitoring System Science Team, corroborated the simplifying assumption that where salinities are unchanged CH_4 emissions are constant with conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increases in removals of 0.001 MMT CO_2 Eq. for the entire time series.

Planned Improvements

The USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the *Inventory*.

N_2O Emissions from Aquaculture in Coastal Wetlands

Shrimp and fish cultivation in coastal areas increases nitrogen loads resulting in direct emissions of N_2O. Nitrous oxide is generated and emitted as a byproduct of the conversion of ammonia (contained in fish urea) to nitrate

through nitrification and nitrate to N_2 gas through denitrification (Hu et al. 2012). Nitrous oxide emissions can be readily estimated from data on fish production (IPCC 2014).

Aquaculture production in the United States has fluctuated slightly from year to year, with resulting N_2O emissions between 0.1 and 0.2 MMT CO_2 Eq. between 1990 and 2022 (Table 6-78). Aquaculture production data were updated through 2019; data through 2022 are not yet available and in this analysis are held constant with 2019 emissions of 0.2 MMT CO_2 Eq. (0.5 Kt N_2O).

Table 6-78: N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq. and kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Emissions (MMT CO_2 Eq.)	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Emissions (kt N_2O)	0.4	0.6	0.5	0.5	0.5	0.5	0.5

Methodology and Time-Series Consistency

The methodology to estimate N_2O emissions from aquaculture in coastal wetlands follows the Tier 1 guidance in the *Wetlands Supplement* by applying country-specific fisheries production data and the IPCC Tier 1 default emission factor.

Each year NOAA Fisheries document the status of U.S. marine fisheries in the annual report of *Fisheries of the United States* (National Marine Fisheries Service 2022), from which activity data for this analysis is derived.[65] The fisheries report has been produced in various forms for more than 100 years, primarily at the national level, on U.S. recreational catch and commercial fisheries landings and values. In addition, data are reported on U.S. aquaculture production, the U.S. seafood processing industry, imports and exports of fish-related products, and domestic supply and per capita consumption of fisheries products. Within the aquaculture chapter, the mass of production for catfish, striped bass, tilapia, trout, crawfish, salmon and shrimp are reported. While some of these fisheries are produced on land and some in open water cages within coastal wetlands, all have data on the quantity of food stock produced, which is the activity data that is applied to the IPCC Tier 1 default emissions factor to estimate emissions of N_2O from aquaculture. It is not apparent from the data as to the amount of aquaculture occurring above the extent of high tides on river floodplains. While some aquaculture occurs on coastal lowland floodplains, this is likely a minor component of tidal aquaculture production because of the need for a regular source of water for pond flushing. The estimation of N_2O emissions from aquaculture is not sensitive to salinity using IPCC approaches, and as such, the location of aquaculture ponds within the boundaries of coastal wetlands does not influence the calculations.

Other open water shellfisheries for which no food stock is provided, and thus no additional N inputs, are not applicable for estimating N_2O emissions (e.g., clams, mussels, and oysters) and have not been included in the analysis. The IPCC Tier 1 default emissions factor of 0.00169 kg N_2O-N per kg of fish/shellfish produced is applied to the activity data to calculate total N_2O emissions.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty estimates are based upon the Tier 1 default 95 percent confidence interval provided in Table 4.15, chapter 4 of the *Wetlands Supplement* for N_2O emissions and on expert judgment of the NOAA *Fisheries of the United States* fisheries production data. Given the overestimate of fisheries production from coastal wetland areas

[65] See https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2020; accessed September August 2023.

due to the inclusion of fish production in non-coastal wetland areas, this is a reasonable initial first approximation for an uncertainty range.

Uncertainty estimates for N_2O emissions from aquaculture production are presented in Table 6-79 for N_2O emissions. The combined uncertainty is 116 percent above and below the estimate of 0.13 MMT CO_2 Eq. In 2022, the total flux was 0.13 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.29 MMT CO_2 Eq.

Table 6-79: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.13	0.00	0.29	-116%	+116%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

NOAA provided internal QA/QC review of reported fisheries data. The coastal wetlands inventory team consulted with the coordinating lead authors of the coastal wetlands chapter of the *Wetlands Supplement* to assess which fisheries production data to include in estimating emissions from aquaculture. It was concluded that N_2O emissions estimates should be applied to any fish production to which food supplement is supplied be they pond or coastal open water and that salinity conditions were not a determining factor in production of N_2O emissions.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Flooded Land Remaining Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural emission of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation, but these waterbodies would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as "reservoirs" or "other constructed waterbodies" (IPCC 2019). Other constructed waterbodies include canals/ditches and ponds (flooded land <8 ha surface area). Reservoirs are defined as flooded land greater than 8 ha. IPCC guidance (IPCC 2019) provides default emission factors for reservoirs, ponds, and canals/ditches.

Land that has been flooded for greater than 20 years is defined as flooded land remaining flooded land and land flooded for 20 years or less is defined as land converted to flooded land. The distinction is based on literature reports that CH_4 and CO_2 emissions are high immediately following flooding, but decline to a steady background level approximately 20 years after flooding (Abril et al. 2005; Barros et al. 2011; Teodoru et al. 2012). Emissions of CH_4 are estimated for flooded land remaining flooded land, but CO_2 emissions are not included as they are

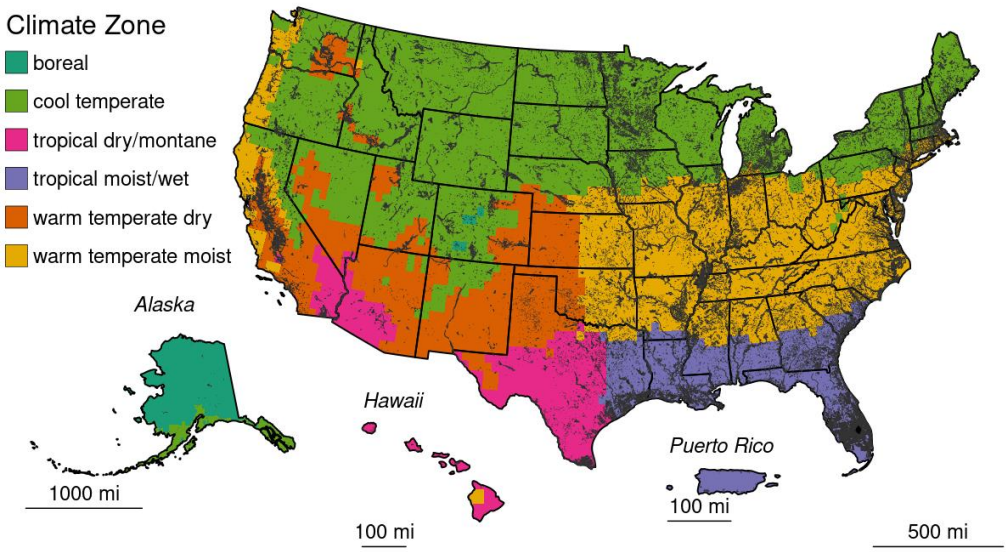
primarily the result of decomposition of organic matter entering the waterbody from the catchment or contained in inundated soils and are captured in Chapter 6, Land Use, Land-Use Change, and Forestry.

Nitrous oxide emissions from flooded lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting of N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

Emissions from Flooded Land Remaining Flooded Land–Reservoirs

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. In 2022, the United States and Puerto Rico hosted 10.2 million ha of reservoir surface area in the flooded land remaining flooded land category (see Methodology and Time-Series Consistency below for calculation details). These reservoirs are distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-10) (IPCC 2019).

Figure 6-10: U.S. Reservoirs (black polygons) in the Flooded Land Remaining Flooded Land Category in 2022



Note: Colors represent climate zone used to derive IPCC default emission factors.

Methane is produced in reservoirs through the microbial breakdown of organic matter. Per unit area, CH_4 emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae), but negatively with system size (i.e., depth, surface area). Methane produced in reservoirs can be emitted from the reservoir surface or exported from the reservoir when CH_4-rich water passes through the dam. This exported CH_4 can be released to the atmosphere as the water passes through hydropower turbines or the downstream river channel. Methane emitted to the atmosphere via this pathway is referred to as "downstream emissions."

Table 6-80 and Table 6-81 below summarize nationally aggregated CH_4 emissions from reservoirs. The increase in CH_4 emissions through the time series is attributable to reservoirs matriculating from the land converted to flooded land category into the flooded land remaining flooded land category.

Table 6-80: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	26.2	27.7	27.9	27.9	27.9	27.9	27.9
Downstream Emission	2.4	2.5	2.5	2.5	2.5	2.5	2.5
Total	**28.6**	**30.2**	**30.4**	**30.4**	**30.4**	**30.4**	**30.4**

Note: Totals may not sum to due independent rounding.

Table 6-81: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	937	989	997	997	997	997	997
Downstream Emission	84	89	90	90	90	90	90
Total	**1,022**	**1,078**	**1,086**	**1,086**	**1,087**	**1,087**	**1,087**

Note: Totals may not sum to due independent rounding.

Methane emissions from reservoirs in Texas, Florida, and Louisiana (Figure 6-11, Table 6-82) compose 34 percent of national CH_4 emissions from reservoirs in 2022. Emissions from these states are particularly high due to 1) the large expanse of reservoirs in these states (Table 6-85) and 2) the high CH_4 emission factor for the tropical dry/montane and topical moist climate zones which encompass a majority of the flooded land area in these states (Figure 6-10, Table 6-83).

Methane emissions from reservoirs in flooded land remaining flooded land increased 6.4 percent from 1990 to 2022 due to the matriculation of reservoirs in land converted to flooded land to flooded land remaining flooded land.

Figure 6-11: Total CH_4 Emissions (Downstream + Surface) from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

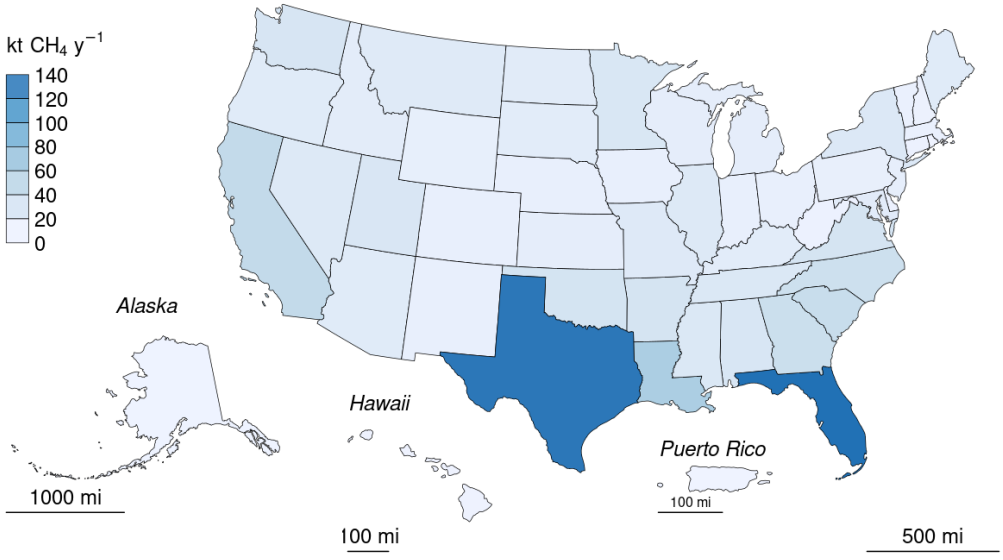


Table 6-82: Surface and Downstream CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

State	Surface	Downstream	Total
Alabama	22	2	24
Alaska	1	+	1
Arizona	14	1	16
Arkansas	25	2	27
California	42	4	46
Colorado	7	1	7
Connecticut	3	+	3
Delaware	3	+	3
District of Columbia	+	+	+
Florida	143	13	155
Georgia	35	3	38
Hawaii	1	+	1
Idaho	12	1	13
Illinois	17	2	19
Indiana	7	1	7
Iowa	7	1	7
Kansas	10	1	11
Kentucky	13	1	14
Louisiana	58	5	64
Maine	14	1	15
Maryland	13	1	14
Massachusetts	5	+	5
Michigan	9	1	10
Minnesota	21	2	23
Mississippi	20	2	21
Missouri	17	1	18
Montana	16	1	17
Nebraska	7	1	7
Nevada	17	2	19
New Hampshire	3	+	4
New Jersey	9	1	9
New Mexico	7	1	7
New York	18	2	20
North Carolina	33	3	36
North Dakota	14	1	15
Ohio	7	1	7
Oklahoma	26	2	28
Oregon	14	1	16
Pennsylvania	7	1	8
Puerto Rico	+	+	+
Rhode Island	1	+	1
South Carolina	38	3	41
South Dakota	12	1	14
Tennessee	20	2	21
Texas	138	12	150
Utah	21	2	23
Vermont	5	+	5
Virginia	25	2	27
Washington	23	2	25
West Virginia	3	+	3
Wisconsin	10	1	11
Wyoming	7	1	8

+ Indicates values less than 0.5 kt.

Methodology and Time-Series Consistency

Estimates of CH_4 emission for reservoirs in flooded land remaining flooded land follow the Tier 1 methodology in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-83). Downstream emissions are calculated as nine percent of the surface emission (Tier 1 default). Total CH_4 emissions from reservoirs are calculated as the sum of surface and downstream emissions. National emissions are calculated as the sum of state emissions.

The IPCC default surface emission factors used in the Tier 1 methodology are derived from model-predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zones are present in the United States.

Table 6-83: IPCC (2019) Default CH_4 Emission Factors for Surface Emission from Reservoirs in Flooded Land Remaining Flooded Land

Climate	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Boreal	0.0136
Cool Temperate	0.054
Warm Temperate Dry	0.1509
Warm Temperate Moist	0.0803
Tropical Dry/Montane	0.2837
Tropical Moist/Wet	0.1411

Note: downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[66] the National Inventory of Dams (NID),[67] the National Wetlands Inventory (NWI),[68] the Navigable Waterways (NW) network,[69] and the EPA's Safe Drinking Water Information System (SDWIS).[70] The NHD only covers the conterminous U.S., whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs: 1) the waterbody was classified as "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to a nearby NID feature (between 100 m to 1000 m), 5) the waterbody intersected a public drinking water intake.

[66] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[67] See https://nid.sec.usace.army.mil.

[68] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[69] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[70] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

EPA assumes that all features included in the NW network are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. Navigable Waterway features greater than 8 ha in surface area are defined as reservoirs.

NWI features were considered "managed" if they had a Special Modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land – other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from the NHD, NWI or NW. If features from the NHD, NWI, or NW datasets overlapped, duplicated areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series.

Figure 6-12: Selected Features from NWI that Meet Flooded Lands Criteria

MODIFIERS

In order to more adequately describe the wetland and deepwater habitats, one each of the water regime, water chemistry, soil, or special modifiers may be applied at the class or lower level in the hierarchy.

Water Regime			Special Modifiers	Water Chemistry		Soil
Nontidal	**Saltwater Tidal**	**Freshwater Tidal**		**Halinity/Salinity**	**pH Modifiers for Fresh Water**	
A Temporarily Flooded	L Subtidal	Q Regularly Flooded-Fresh Tidal	b Beaver	1 Hyperhaline / Hypersaline	a Acid	g Organic
B Seasonally Saturated	M Irregularly Exposed	R Seasonally Flooded-Fresh Tidal	d Partly Drained/Ditched	2 Euhaline / Eusaline	t Circumneutral	n Mineral
C Seasonally Flooded	N Regularly Flooded	S Temporarily Flooded- Fresh Tidal	f Farmed	3 Mixohaline / M ixosaline (Brackish)	i Alkaline	
D Continuously Saturated	P Irregularly Flooded	T Semipermanently Flooded-Fresh Tidal	m Managed	4 Polyhaline		
E Seasonally Flooded / Saturated		V Permanently Flooded-Fresh Tidal	h Diked/Impounded	5 Mesohaline		
F Semipermanently Flooded			r Artificial Substrate	6 Oligohaline		
G Intermittently Exposed			s Spoil	0 Fresh		
H Permanently Flooded			x Excavated			
J Intermittently Flooded						
K Artificially Flooded						

Must also meet one selected special modifier (red box) to be included in the flooded lands inventory

Included in the flooded lands inventory if it meets water regime qualifier (gold box)

Source (modified): https://www.fws.gov/sites/default/files/documents/wetlands-and-deepwater-map-code-diagram.pdf

IPCC (2019) allows for the exclusion of managed waterbodies from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[71]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the inventory.

[71] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

The surface area of reservoirs in flooded land remaining flooded land increased by approximately 6 percent from 1990 to 2022 (Table 6-84) due to reservoirs matriculating into flooded land remaining flooded land when they reached 20 years of age.

Table 6-84: National Totals of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

Surface Area (millions of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	9.6	10.1	10.2	10.2	10.2	10.2	10.2

Table 6-85: State Breakdown of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	0.22	0.23	0.23	0.23	0.23	0.23	0.23
Alaska	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arizona	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Arkansas	0.28	0.29	0.29	0.29	0.29	0.29	0.29
California	0.37	0.39	0.39	0.39	0.39	0.39	0.39
Colorado	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Connecticut	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Delaware	0.03	0.03	0.03	0.03	0.03	0.03	0.03
District of Columbia	+	+	+	+	+	+	+
Florida	0.98	1.01	1.01	1.01	1.01	1.01	1.01
Georgia	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Hawaii	+	+	+	+	+	+	+
Idaho	0.17	0.19	0.19	0.19	0.19	0.19	0.19
Illinois	0.17	0.18	0.22	0.22	0.22	0.22	0.22
Indiana	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Iowa	0.08	0.09	0.10	0.10	0.10	0.10	0.10
Kansas	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Kentucky	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Louisiana	0.40	0.41	0.41	0.41	0.41	0.41	0.41
Maine	0.25	0.26	0.26	0.26	0.26	0.26	0.26
Maryland	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Massachusetts	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Michigan	0.16	0.17	0.17	0.17	0.17	0.17	0.17
Minnesota	0.38	0.38	0.39	0.39	0.39	0.39	0.39
Mississippi	0.18	0.19	0.19	0.19	0.19	0.19	0.19
Missouri	0.19	0.21	0.21	0.21	0.21	0.21	0.21
Montana	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Nebraska	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Nevada	0.09	0.09	0.09	0.09	0.09	0.09	0.09
New Hampshire	0.06	0.06	0.06	0.06	0.06	0.06	0.06
New Jersey	0.11	0.11	0.11	0.11	0.11	0.11	0.11
New Mexico	0.05	0.05	0.05	0.05	0.05	0.05	0.05
New York	0.31	0.32	0.32	0.32	0.32	0.32	0.32
North Carolina	0.39	0.41	0.41	0.41	0.41	0.41	0.41
North Dakota	0.10	0.25	0.26	0.26	0.26	0.26	0.26
Ohio	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Oklahoma	0.24	0.27	0.27	0.27	0.27	0.27	0.27
Oregon	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Pennsylvania	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Puerto Rico	+	+	+	+	+	+	+
Rhode Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02
South Carolina	0.31	0.32	0.33	0.33	0.33	0.33	0.33

South Dakota	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Tennessee	0.18	0.24	0.24	0.24	0.24	0.24	0.24
Texas	0.63	0.70	0.71	0.71	0.71	0.71	0.71
Utah	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Vermont	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Virginia	0.30	0.31	0.31	0.31	0.31	0.31	0.31
Washington	0.24	0.24	0.24	0.24	0.24	0.24	0.24
West Virginia	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Wisconsin	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Wyoming	0.12	0.13	0.14	0.14	0.14	0.14	0.14
Total	**9.47**	**10.10**	**10.20**	**10.20**	**10.20**	**10.20**	**10.20**

+ Indicates values less than 0.005 million ha.

Note: Totals may not sum due to independent rounding.

Uncertainty

Uncertainty in estimates of CH_4 emissions from reservoirs in flooded land remaining flooded land (Table 6-86) are developed using Monte Carlo simulations (IPCC Approach 2) and include uncertainty in the default emission factors and land areas. Each iteration of the simulation draws surface and downstream emission factors from a statistical distribution based on the mean and variance in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). The CH_4 emission factors for surface and downstream emissions are modeled using normal and lognormal distributions, respectively. The 2019 IPCC Refinement does not contain sufficient information to define a normal distribution for the CO_2 emission factor and a uniform distribution bounded by the 95% confidence internal of the mean is assumed. Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 - 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the reservoir area estimates is assumed and is based on expert judgment. Each iteration of the simulation draws a surface area for each waterbody from a uniform distribution bounded by ± 15 percent of the estimated surface area.

Table 6-86: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	27.9	27.4	28.4	-1.7%	+1.7%
Downstream	CH_4	2.5	2.4	3.1	-5.6%	+22.4%
Total	**CH_4**	**30.4**	**29.9**	**31.3**	**-1.6%**	**+2.9%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration with many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of

the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 emission estimates from reservoirs of 1.23 MMT CO_2 Eq., or 4 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[72] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

Emissions from Flooded Land Remaining Flooded Land–Other Constructed Waterbodies

The IPCC (IPCC 2019) provides emission factors for several types of "other constructed waterbodies" including freshwater ponds and canals/ditches. IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." Furthermore, the IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) defines a size threshold of 8 ha to distinguish reservoirs from "other constructed waterbodies." For this *Inventory*, ponds are defined as managed flooded land that are 1) less than 8 ha in surface area, and 2) not categorized as canals/ditches. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emissions than the latter. Activity data on pond salinity are not uniformly available for the conterminous United States and all ponds in the inventory are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are often sites of substantial CH_4 emissions from anaerobic sediments.

Canals and ditches (terms are used interchangeably) are linear water features constructed to transport water (i.e., stormwater drainage, aqueduct), to irrigate or drain land, to connect two or more bodies of water, or to serve as a

[72] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

waterway for watercraft. The geometry and construction of canals and ditches varies widely and includes narrow earthen channels (<1 m wide) and concrete lined aqueducts in excess of 50 m wide. Canals and ditches can be extensive in many agricultural, forest and settlement areas, and may also be significant sources of emissions in some circumstances.

Methane emissions from freshwater ponds in flooded land remaining flooded land increased by approximately 1 percent from 1990 to 2022. Methane emissions from canals and ditches have remained constant throughout the time series because age data are not available for canals and ditches, thus they are assumed to be greater than 20-years old in 1990 and are included in flooded land remaining flooded land throughout the time series. Overall, CH_4 emissions from other constructed waterbodies have remained fairly constant since 1990 (Table 6-87 and Table 6-88).

Table 6-87: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Freshwater Ponds	11.4	11.5	11.5	11.5	11.5	11.5	11.5
Total	**13.7**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**

Note: Totals may not sum due to independent rounding.

Table 6-88: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	80.9	80.9	80.9	80.9	80.9	80.9	80.9
Freshwater Ponds	406.6	411.0	411.7	411.8	411.8	411.8	411.9
Total	**487.5**	**491.9**	**492.6**	**492.6**	**492.7**	**492.7**	**492.7**

Note: Totals may not sum due to independent rounding.

Florida and Louisiana have the greatest methane emissions from canals and ditches in the United States (Figure 6-13, Table 6-89). Presumably, most of these canals serve to drain the extensive wetland complexes in these states (Davis, 1973). California has the third greatest methane emissions from canals and ditches. Canals and ditches in California primarily serve to convey water from the mountains to urban and agricultural areas. Michigan and Minnesota have the fourth and fifth largest methane emissions from canals and ditches. These systems serve to drain historic wetlands to facilitate row-crop agriculture. Texas, Florida, and Georgia have the greatest methane emissions from freshwater ponds, although states throughout the eastern United States make significant contributions to the national total. These patterns of emissions are in accordance with the distribution of other constructed waterbodies in the United States.

Table 6-89: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

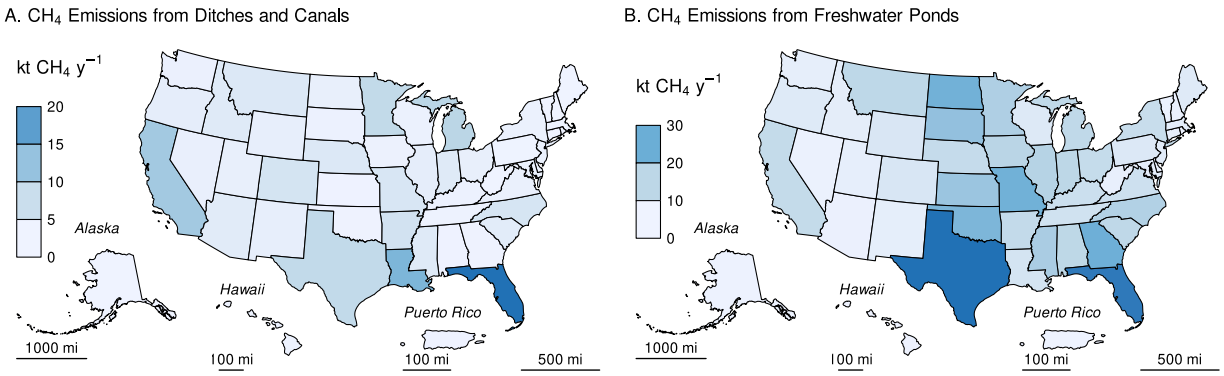
State	Canals and Ditches	Freshwater Ponds	Total
Alabama	+	10.5	10.6
Alaska	+	+	+
Arizona	1.5	1.0	2.4
Arkansas	3.1	9.4	12.4
California	7.0	9.2	16.2
Colorado	2.9	4.8	7.7
Connecticut	+	1.8	1.8
Delaware	+	0.9	0.9
District of Columbia	+	+	+

Florida	15.6	30.7	46.2
Georgia	+	21.0	21.2
Hawaii	+	+	0.5
Idaho	1.7	2.4	4.1
Illinois	1.0	11.7	12.8
Indiana	1.7	10.6	12.3
Iowa	+	11.2	11.6
Kansas	+	15.4	15.5
Kentucky	+	7.7	7.9
Louisiana	9.4	5.9	15.3
Maine	+	3.5	3.5
Maryland	+	2.3	2.7
Massachusetts	+	2.3	2.3
Michigan	5.4	10.0	15.4
Minnesota	4.7	12.7	17.3
Mississippi	1.6	13.4	15.1
Missouri	2.4	20.7	23.1
Montana	2.0	10.5	12.5
Nebraska	2.0	9.1	11.1
Nevada	0.7	0.8	1.5
New Hampshire	+	1.0	1.1
New Jersey	+	3.0	3.4
New Mexico	0.8	2.1	2.9
New York	+	8.3	8.7
North Carolina	2.6	12.2	14.8
North Dakota	0.8	20.6	21.3
Ohio	0.8	8.9	9.7
Oklahoma	+	19.3	19.4
Oregon	1.0	3.6	4.6
Pennsylvania	+	4.1	4.1
Puerto Rico	+	+	+
Rhode Island	+	+	+
South Carolina	1.3	10.4	11.7
South Dakota	+	16.6	16.9
Tennessee	+	6.7	6.8
Texas	4.6	32.1	36.8
Utah	0.8	2.0	2.8
Vermont	+	0.8	0.8
Virginia	0.5	7.3	7.9
Washington	+	2.0	2.5
West Virginia	+	1.5	1.5
Wisconsin	+	3.8	4.2
Wyoming	0.9	4.8	5.7
Total	**80.9**	**411.9**	**492.7**

+ Indicates values less than 0.5 kt.

Note: Totals may not sum due to independent rounding.

Figure 6-13: 2022 CH_4 Emissions from A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (kt CH_4)



Methodology and Time-Series Consistency

Estimates of CH_4 emissions for other constructed waterbodies in flooded land remaining flooded Land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Based on IPCC guidance, methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-90). Although literature data on greenhouse gas emissions from canals and ditches is relatively sparse, they have the highest default emission factor of all flooded land types (Table 6-90). Default emission factors for freshwater ponds are on the higher end of those for reservoirs. There are insufficient data to support climate-specific emission factors for ponds or canals and ditches. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-90: IPCC (2019) Default CH_4 Emission Factors for Surface Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Other Constructed Waterbody	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Freshwater ponds	0.183
Canals and ditches	0.416

Area estimates

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[73] the National Inventory of Dams (NID),[74] the National Wetlands Inventory (NWI),[75] the Navigable Waterways (NW) network,[76] and the EPA's Safe Drinking Water Information System (SDWIS).[77] The NHD

[73] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[74] See https://nid.sec.usace.army.mil.

[75] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[76] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[77] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, District of Columbia, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were greater than 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in flooded land remaining flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m), the waterbody intersected a drinking water intake.

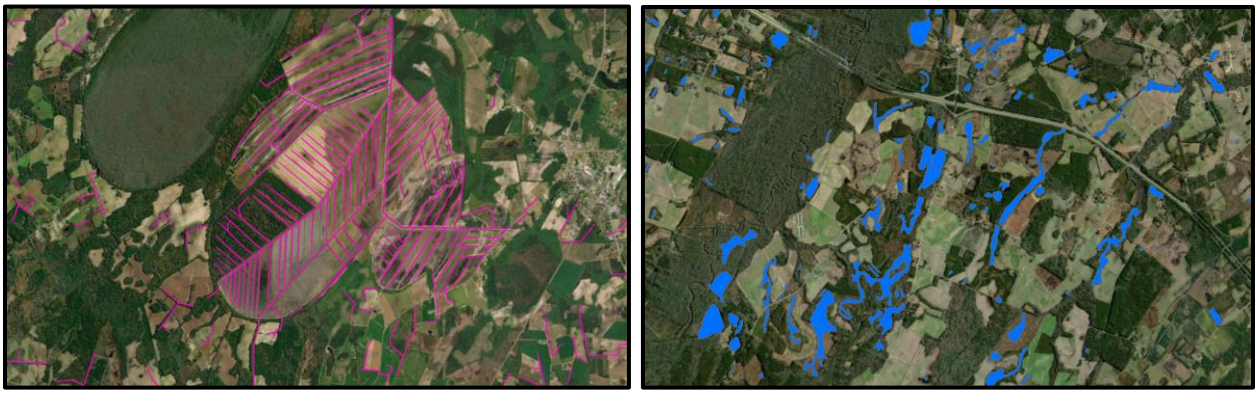
EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch (see below) were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Canals and ditches, a subset of other constructed waterbodies, were identified in the NWI by their morphology. Unlike a natural water body, canals and ditches are typically narrow, linear features with abrupt angular turns. Figure 6-14 contrasts the unique shape of ditches/canals vs more natural water features.

Figure 6-14: Left: NWI Features Identified as Canals/Ditches (pink) by Unique Narrow, Linear/Angular Morphology. Right: Non-Canal/Ditches with More Natural Morphology (blue)



This morphology was identified systematically using shape attributes in a decision tree model. A training set of 752 features were identified as either "ditch" or "not ditch" using expert judgment. The training set was used to train a decision tree which was used to categorize millions of NWI features based on three shape attribute ratios (Figure 6-12).

Table 6-91: Predictors used in Decision Tree to Identify Canal/Ditches

Shape Length : # of Shape Vertices
Shape Area : Shape Length
Shape Area : # of Shape Vertices

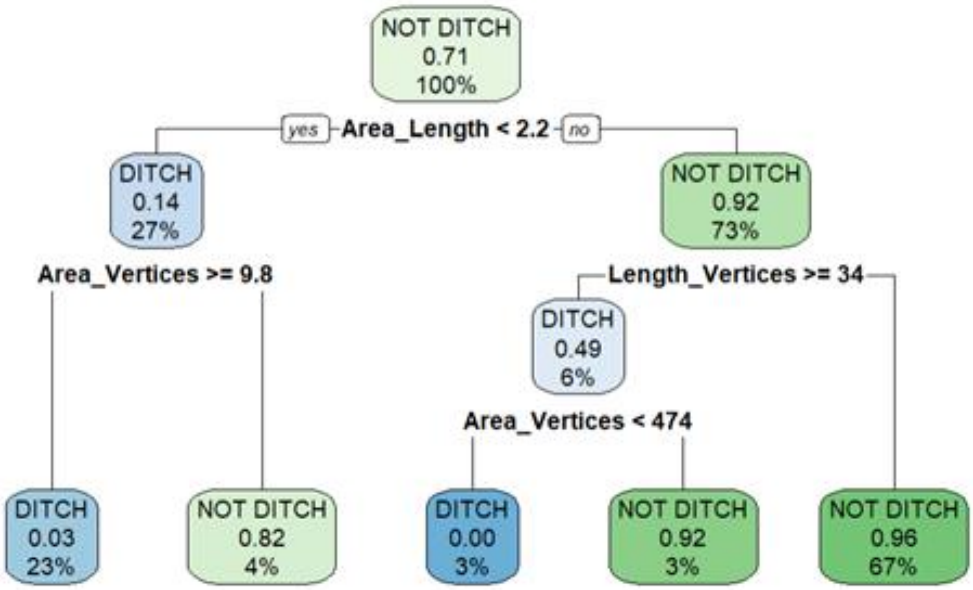
The decision tree built a model using 80 percent of the 752 training features and used the 20 percent to validate the model. The model was 93.1 percent accurate. Below are the validation results (Table 6-92).

Table 6-92: Validation Results for Ditch/Canal Classification Decision Tree

	Truth	
Prediction	Ditch/Canal	Not Ditch/Canal
Ditch/Canal	49	5
Not Ditch/Canal	8	27

The decision tree model was then applied to the entire NWI dataset using the following shape attribute ratios (Figure 6-15).

Figure 6-15: Structure of Decision Tree Used to Identify Canals/Ditches



Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, these areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 2,250,662 ha of freshwater ponds and 194,412 ha of canals and ditches in flooded land remaining flooded land (Table 6-93). The surface area of freshwater ponds increased by 28,632 ha (1.3 percent) from 1990 to 2022 due to flooded lands matriculating from land converted to flooded land to flooded land remaining flooded land. All canals and ditches were assumed to be greater than 20-years old throughout the time series, thus the surface area of these flooded lands is constant throughout the time series.

Table 6-93: National Surface Area Totals in Flooded Land Remaining Flooded Land - Other Constructed Waterbodies (ha)

	1990	2005	2018	2019	2020	2021	2022
Canals and ditches	194,412	194,412	194,412	194,412	194,412	194,412	194,412
Freshwater ponds	2,222,030	2,245,881	2,249,672	2,250,007	2,250,337	2,250,540	2,250,662
Total	**2,416,442**	**2,440,292**	**2,444,084**	**2,444,418**	**2,444,749**	**2,444,951**	**2,445,074**

Note: Totals may not sum due to independent rounding.

Canals and ditches in the conterminous United States are most abundant in the Gulf Coast states and California (Figure 6-16A, Table). Florida contains 19 percent of all U.S. canal and ditch surface area, most of which were constructed in the early 1900s for drainage, flood protection, and water storage purposes. Freshwater ponds are more widely distributed across the United States (Figure 6-16B, Table 6-95). Texas has the greatest surface area of freshwater ponds, equivalent to 8 percent of all freshwater pond surface area in the United States, closely followed by Florida.

Figure 6-16: 2022 Surface Area of A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (ha)

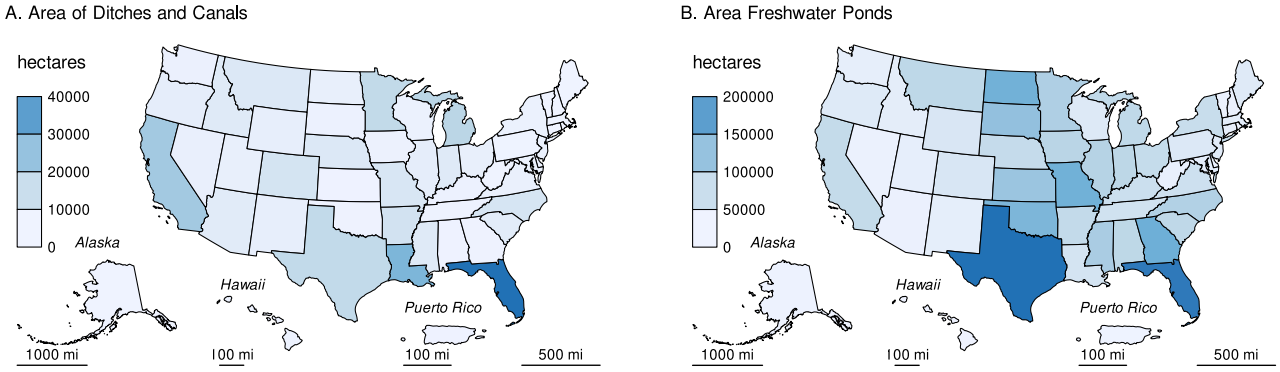


Table 6-94: State Totals of Surface Area in Flooded Land Remaining Flooded Land— Canals and Ditches (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	228	228	228	228	228	228	228
Alaska	115	115	115	115	115	115	115
Arizona	3,536	3,536	3,536	3,536	3,536	3,536	3,536
Arkansas	7,349	7,349	7,349	7,349	7,349	7,349	7,349
California	16,725	16,725	16,725	16,725	16,725	16,725	16,725
Colorado	6,874	6,874	6,874	6,874	6,874	6,874	6,874
Connecticut	28	28	28	28	28	28	28
Delaware	130	130	130	130	130	130	130
District of Columbia	1	1	1	1	1	1	1
Florida	37,482	37,482	37,482	37,482	37,482	37,482	37,482
Georgia	352	352	352	352	352	352	352

Hawaii	538	538	538	538	538	538	538
Idaho	4,027	4,027	4,027	4,027	4,027	4,027	4,027
Illinois	2,489	2,489	2,489	2,489	2,489	2,489	2,489
Indiana	4,064	4,064	4,064	4,064	4,064	4,064	4,064
Iowa	867	867	867	867	867	867	867
Kansas	258	258	258	258	258	258	258
Kentucky	672	672	672	672	672	672	672
Louisiana	22,565	22,565	22,565	22,565	22,565	22,565	22,565
Maine	56	56	56	56	56	56	56
Maryland	967	967	967	967	967	967	967
Massachusetts	132	132	132	132	132	132	132
Michigan	12,897	12,897	12,897	12,897	12,897	12,897	12,897
Minnesota	11,235	11,235	11,235	11,235	11,235	11,235	11,235
Mississippi	3,936	3,936	3,936	3,936	3,936	3,936	3,936
Missouri	5,670	5,670	5,670	5,670	5,670	5,670	5,670
Montana	4,740	4,740	4,740	4,740	4,740	4,740	4,740
Nebraska	4,864	4,864	4,864	4,864	4,864	4,864	4,864
Nevada	1,587	1,587	1,587	1,587	1,587	1,587	1,587
New Hampshire	103	103	103	103	103	103	103
New Jersey	944	944	944	944	944	944	944
New Mexico	2,002	2,002	2,002	2,002	2,002	2,002	2,002
New York	925	925	925	925	925	925	925
North Carolina	6,321	6,321	6,321	6,321	6,321	6,321	6,321
North Dakota	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Ohio	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Oklahoma	278	278	278	278	278	278	278
Oregon	2,498	2,498	2,498	2,498	2,498	2,498	2,498
Pennsylvania	143	143	143	143	143	143	143
Puerto Rico	249	249	249	249	249	249	249
Rhode Island	1	1	1	1	1	1	1
South Carolina	3,226	3,226	3,226	3,226	3,226	3,226	3,226
South Dakota	703	703	703	703	703	703	703
Tennessee	442	442	442	442	442	442	442
Texas	11,152	11,152	11,152	11,152	11,152	11,152	11,152
Utah	1,875	1,875	1,875	1,875	1,875	1,875	1,875
Vermont	95	95	95	95	95	95	95
Virginia	1,306	1,306	1,306	1,306	1,306	1,306	1,306
Washington	1,125	1,125	1,125	1,125	1,125	1,125	1,125
West Virginia	28	28	28	28	28	28	28
Wisconsin	887	887	887	887	887	887	887
Wyoming	2,086	2,086	2,086	2,086	2,086	2,086	2,086
Total	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**

Table 6-95: State Totals of Surface Area in Flooded Land Remaining Flooded Land—Freshwater Ponds (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	57,034	57,342	57,355	57,355	57,355	57,355	57,355
Alaska	2,367	2,370	2,370	2,370	2,370	2,370	2,370
Arizona	5,199	5,236	5,249	5,249	5,253	5,253	5,253
Arkansas	50,880	51,211	51,211	51,211	51,211	51,211	51,211
California	50,219	50,426	50,499	50,504	50,511	50,513	50,519
Colorado	26,174	26,448	26,478	26,479	26,480	26,480	26,494
Connecticut	9,630	9,697	9,699	9,699	9,699	9,699	9,699
Delaware	4,717	4,721	4,721	4,721	4,721	4,721	4,721
District of Columbia	16	16	16	16	16	16	16
Florida	167,317	167,453	167,496	167,502	167,502	167,508	167,508

Georgia	113,254	114,898	114,969	114,972	114,972	114,972	114,972
Hawaii	1,580	1,592	1,595	1,595	1,595	1,595	1,595
Idaho	13,220	13,352	13,359	13,359	13,359	13,360	13,360
Illinois	63,516	64,044	64,144	64,149	64,159	64,160	64,169
Indiana	57,593	58,065	58,170	58,175	58,175	58,175	58,185
Iowa	57,450	59,612	60,745	60,929	61,051	61,147	61,168
Kansas	81,828	83,900	83,976	83,985	83,985	84,002	84,004
Kentucky	41,427	41,808	41,837	41,837	41,837	41,837	41,837
Louisiana	32,085	32,210	32,221	32,221	32,226	32,226	32,226
Maine	19,102	19,149	19,159	19,159	19,159	19,159	19,159
Maryland	12,569	12,739	12,810	12,810	12,812	12,815	12,818
Massachusetts	12,359	12,413	12,457	12,464	12,470	12,472	12,476
Michigan	54,525	54,672	54,701	54,701	54,709	54,709	54,709
Minnesota	68,801	69,082	69,173	69,176	69,202	69,210	69,220
Mississippi	72,832	73,209	73,336	73,343	73,363	73,375	73,383
Missouri	109,573	112,993	113,068	113,071	113,073	113,077	113,079
Montana	56,860	57,246	57,263	57,268	57,269	57,269	57,269
Nebraska	48,051	49,380	49,649	49,667	49,697	49,706	49,709
Nevada	4,452	4,455	4,508	4,509	4,512	4,512	4,515
New Hampshire	5,427	5,526	5,585	5,585	5,586	5,587	5,587
New Jersey	16,192	16,232	16,253	16,253	16,253	16,253	16,253
New Mexico	11,379	11,394	11,398	11,401	11,401	11,401	11,406
New York	45,224	45,485	45,590	45,592	45,592	45,598	45,598
North Carolina	66,205	66,661	66,744	66,744	66,747	66,750	66,751
North Dakota	112,310	112,384	112,469	112,475	112,485	112,489	112,492
Ohio	48,028	48,393	48,591	48,605	48,637	48,651	48,656
Oklahoma	103,243	105,224	105,288	105,304	105,318	105,324	105,333
Oregon	19,304	19,487	19,532	19,534	19,539	19,539	19,539
Pennsylvania	22,018	22,256	22,289	22,289	22,289	22,289	22,289
Puerto Rico	708	708	708	708	708	708	708
Rhode Island	2,204	2,213	2,220	2,220	2,220	2,220	2,220
South Carolina	55,794	56,456	56,673	56,682	56,686	56,686	56,686
South Dakota	90,237	90,447	90,504	90,515	90,516	90,521	90,521
Tennessee	35,927	36,307	36,332	36,337	36,343	36,344	36,344
Texas	172,580	175,497	175,569	175,574	175,575	175,575	175,575
Utah	10,703	10,764	10,772	10,772	10,773	10,773	10,773
Vermont	4,316	4,381	4,392	4,392	4,392	4,392	4,392
Virginia	39,938	39,996	40,000	40,000	40,000	40,000	40,000
Washington	10,943	11,081	11,119	11,119	11,122	11,123	11,123
West Virginia	8,027	8,156	8,166	8,166	8,166	8,166	8,166
Wisconsin	20,845	20,989	21,003	21,003	21,003	21,003	21,003
Wyoming	25,851	26,106	26,243	26,243	26,244	26,246	26,250
Total	**2,222,030**	**2,245,881**	**2,249,672**	**2,250,007**	**2,250,337**	**2,250,540**	**2,250,662**

Uncertainty

Uncertainty in estimates of CH_4 emissions from other constructed waterbodies (ponds, canals/ditches) in flooded land remaining flooded land (Table 6-96) are estimated using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in default emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-96: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Canals and ditches	CH_4	2.3	2.1	2.4	-5.1%	+7.0%
Freshwater pond	CH_4	11.5	11.5	11.5	-0.04%	+0.04%
Total	**CH_4**	**13.8**	**13.7**	**13.9**	**-0.8%**	**+1.0%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID.[78] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current (1990 through 2022) *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual decrease in CH_4 emission estimates from other constructed waterbodies of 2.7 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

[78] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

Planned Improvements

Default emission factors for canals/ditches were derived from a global dataset that include few measurements from U.S. systems. The EPA plans to conduct a literature survey to determine if sufficient data are available to derive a country-specific emission factor for the 1990 through 2024 *Inventory* submission.

Canal and ditch surface area included here may overlap with ditches and canals included in CH_4 emission estimates for ditches draining inland organic soils (IPCC 2013, section 2.2.2.1). EPA plans to reconcile ditch/canal surface areas between the two managed land types (flooded land vs drained inland organic soils) in the next (i.e., 1990 through 2023) *Inventory*.

Features less than 8 ha in the NW that were not identified as Canal/Ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.9 Land Converted to Wetlands (CRT Source Category 4D2)

Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Land converted to vegetated coastal wetlands occurs as a result of inundation of unprotected low-lying coastal areas with gradual sea-level rise, flooding of previously drained land behind hydrological barriers, and through active restoration and creation of coastal wetlands through removal of hydrological barriers. Based upon NOAA C-CAP, wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into emergent marsh, scrub shrub and forest classes All other land categories (i.e., forest land, cropland, grassland, settlements and other lands) are identified as having some area converting to vegetated coastal wetlands. This *Inventory* does not include land converted to unvegetated open water coastal wetlands (see Planned Improvements section below). Between 1990 and 2022 the rate of annual transition for land converted to vegetated coastal wetlands ranged from 0 to 2,650 ha per year, depending on the type of land converted.[79] Conversion rates from forest land were relatively consistent between 1990 and 2010 (ranging between 2,409 and 2,650 ha) and decreased to 625 ha starting in 2011; the majority of these conversions resulted in increases in the area of palustrine wetlands, which also initiates CH_4 emissions when lands are inundated with fresh water.[80] Little to no conversion of cropland, grassland, settlement, or other lands to vegetated coastal wetlands occurred during the reporting period, with converted areas ranging from 0 to 25 ha per year.[81]

[79] Data from C-CAP; see https://coast.noaa.gov/digitalcoast/tools/. Accessed October 2023.

[80] Currently, the C-CAP dataset categorizes coastal wetlands as either palustrine (fresh water) or estuarine (presence of saline water). This classification does not differentiate between estuarine wetlands with salinity ≤ 18 ppt (when methanogenesis begins to occur) and those that are >18 ppt (where negligible to no CH_4 is produced); therefore, it is not possible at this time to account for CH_4 emissions from estuarine wetlands in the *Inventory*.

[81] At the present stage of *Inventory* development, coastal wetlands are not explicitly shown in the land representation analysis (Section 6.1) while work continues harmonizing data from NOAA's Coastal Change Analysis Program (C-CAP) with NRI, FIA and NLDC data used to compile the land representation (NOAA OCM 2020).

Conversion to coastal wetlands resulted in a biomass carbon stock loss of 0.2 MMT CO_2 Eq. (0.03 MMT C) in 2022 (Table 6-97 and Table 6-98). Loss of forest biomass through conversion of forest lands to vegetated coastal wetlands is the primary driver behind biomass carbon stock change being a source rather than a sink across the time series. Conversion of cropland, grassland, settlement and other lands result in a net increase in biomass stocks. Conversion of lands to vegetated coastal wetlands resulted in a DOM loss of 0.03 MMT CO_2 Eq. (0.008 MMT C) in 2022 (Table 6-97 and Table 6-98), which is driven by the loss of DOM when forest land is converted to vegetated coastal wetlands. This is likely an overestimate of loss because wetlands inherently preserve dead organic material. Conversion of cropland, grassland, settlement and other land results in a net increase in DOM Across all time periods, soil carbon accumulation resulting from lands converted to vegetated coastal wetlands is a carbon sink and has ranged between -0.14 and -0.3 MMT CO_2 Eq. (-0.04 and -0.07 MMT C; Table 6-97 and Table 6-98). Conversion of lands to coastal wetlands resulted in CH_4 emissions of 0.17 MMT CO_2 Eq. (6.1 kt CH_4) in 2022 (Table 6-99). Methane emissions due to the conversion of lands to vegetated coastal wetlands are largely the result of forest land converting to palustrine emergent and scrub shrub coastal wetlands in warm temperate climates. Emissions were the highest between 1990 and 2002 (0.28 MMT CO_2 Eq., 10.0 kt CH_4) and have continually decreased to current levels. This decrease was driven by a reduction in the rate of conversion of forest land to palustrine scrub-shrubs and emergent wetlands.

Table 6-97: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.49**	**0.50**	**(+)**	**0.01**	**0.02**	**0.03**	**0.04**
Biomass C Stock	0.62	0.62	0.13	0.13	0.13	0.13	0.13
Dead Organic Matter C Flux	0.11	0.12	0.03	0.03	0.03	0.03	0.03
Soil C Stock	(0.24)	(0.24)	(0.16)	(0.15)	(0.14)	(0.13)	(0.12)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.03)**	**(0.03)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**
Biomass C Stock	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soil C Stock	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.60**	**0.60**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Total Dead Organic Matter Flux	**0.11**	**0.12**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Soil C Flux	**(0.25)**	**(0.25)**	**(0.18)**	**(0.17)**	**(0.16)**	**(0.15)**	**(0.14)**
Total Flux	**0.46**	**0.47**	**(0.02)**	**(0.02)**	**(0.01)**	**0.00**	**0.01**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-98: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**

Wetlands							
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.13**	**0.14**	**+**	**+**	**0.006**	**0.008**	**0.01**
Biomass C Stock	0.17	0.17	0.04	0.04	0.04	0.04	0.04
Dead Organic Matter C Flux	0.03	0.03	0.01	0.01	0.01	0.01	0.01
Soil C Stock	(0.06)	(0.06)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**()**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**
Biomass C Stock	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.16**	**0.16**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Dead Organic Matter Flux	**0.03**	**0.03**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total Soil C Flux	**(0.07)**	**(0.07)**	**(0.05)**	**(0.05)**	**(0.04)**	**(0.04)**	**(0.04)**
Total Flux	**0.13**	**0.13**	**(0.01)**	**(+)**	**(+)**	**+**	**+**

+ Absolute value does not exceed 0.005 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-99: CH_4 Emissions from Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	+	0.01	0.04	0.04	0.05	0.05	0.05
Forest Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	0.28	0.27	0.19	0.18	0.17	0.16	0.15
CH_4 Emissions (kt CH_4)	9.88	9.74	6.85	6.48	6.10	5.76	5.41
Grassland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	0.01	0.07	0.07	0.08	0.08	0.09
Other Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	0.01	0.01	0.01	0.01	0.02
CH_4 Emissions (kt CH_4)	0.08	0.14	0.43	0.47	0.50	0.52	0.54
Settlements Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	+	+	+	+	+	+
Total CH_4 Emissions (MMT CO_2 Eq.)	**0.28**	**0.28**	**0.21**	**0.20**	**0.19**	**0.18**	**0.17**
Total CH_4 Emissions (kt CH_4)	**9.98**	**9.91**	**7.39**	**7.06**	**6.73**	**6.41**	**6.09**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq. or 0.005 kt CH_4.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section provides a description of the methodology used to estimate changes in biomass, dead organic matter and soil carbon stocks and CH_4 emissions for land converted to vegetated coastal wetlands. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Biomass Carbon Stock Changes

Biomass carbon stocks for land converted to vegetated coastal wetlands are estimated for palustrine and estuarine marshes for land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants within the U.S. land representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). Both federal and non-federal lands are represented. Delineating vegetated coastal wetlands from ephemerally flooded upland grasslands represents a particular challenge in remote sensing. Moreover, at the boundary between wetlands and uplands, which may be gradual on low lying coastlines, the presence of wetlands may be ephemeral depending upon weather and climate cycles and as such, impacts on the emissions and removals will vary over these time frames. Trends in land cover change are extrapolated to 1990 and 2021 from these datasets using the C-CAP change data closest in date to a given year. Biomass is not sensitive to soil organic content. Aboveground biomass carbon stocks for non-forested coastal wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). Aboveground biomass carbon removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class. The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[82]). Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (IPCC 2014) and summed with aboveground biomass to obtain total biomass carbon stocks. Aboveground biomass carbon stocks for forest land, cropland, and grassland that are lost with the conversion to vegetated coastal wetlands were derived from Tier 1 default values (IPCC 2006; IPCC 2019). Biomass carbon stock changes are calculated by subtracting the biomass carbon stock values of each land use category (i.e., forest land, cropland, and grassland) from those of vegetated coastal wetlands in each climate zone and multiplying that value by the corresponding C-CAP derived area gained that year in each climate zone. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The total coastal wetland biomass carbon stock change is accounted for during the year of conversion; therefore, no interannual changes are calculated during the remaining years it is in the category.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are accounted for in subtropical estuarine forested wetlands for lands converted to vegetated coastal wetlands across all years. Tier 1 estimates of mangrove DOM carbon stocks were used for subtropical estuarine forested wetlands (IPCC 2014). Neither Tier 1 or 2 data on DOM are currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone or estuarine forested wetlands in climates other than subtropical climates. Tier 1 DOM C stocks for forest land converted to vegetated coastal wetlands were derived from IPCC (2019) to account for the loss of DOM that occurs with conversion. Changes in DOM are assumed to be negligible for other land use conversions (i.e., other than forest land) to coastal wetlands based on the Tier 1 method in IPCC (2006). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2022 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by the

[82] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed October 2023.

difference between Tier 1 DOM carbon stocks for vegetated coastal wetlands and forest land. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The coastal wetland DOM stock is assumed to be in steady state once established in the year of conversion; therefore, no interannual changes are calculated.

Soil Carbon Stock Changes

Soil carbon removals are estimated for land converted to vegetated coastal wetlands across all years. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature[83] (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). To estimate soil carbon stock changes, no differentiation is made for soil type (i.e., mineral, organic). Soil C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class.

As per IPCC (2014) guidance, land converted to vegetated coastal wetlands is assumed to remain in this category for up to 20 years before transitioning to vegetated coastal wetlands remaining vegetated coastal wetlands. Tier 2 level estimates of soil carbon stock changes associated with annual soil carbon accumulation from land converted to vegetated coastal wetlands were developed using country-specific soil carbon removal factors multiplied by activity data of land area for land converted to vegetated coastal wetlands for a given year in addition to the previous 19-year cumulative area. Guidance from the *Wetlands Supplement* allows for the rate of soil carbon accumulation to be instantaneously equivalent to that in natural settings and that soil carbon accumulation is initiated when natural vegetation becomes established; this is assumed to occur in the first year of conversion. No loss of soil carbon as a result of land conversion to coastal wetlands is assumed to occur. Since the C-CAP coastal wetland area dataset begins in 1996, the area converted prior to 1996 is assumed to be the same as in 1996. Similarly, the coastal wetland area data for 2017 through 2022 is assumed to be the same as in 2016. The methodology follows Eq. 4.7, Chapter 4 of the *IPCC Wetlands Supplement* (IPCC 2014) and is applied to the area of land converted to vegetated coastal wetlands on an annual basis.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for land converted to vegetated coastal wetlands are derived from the same wetland map used in the analysis of wetland soil carbon fluxes for palustrine wetlands, and are produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *IPCC Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *IPCC Wetlands Supplement* and a global warming potential of 28 is used (IPCC 2013). Because land converted to vegetated coastal wetlands is held in this category for up to 20 years before transitioning to vegetated coastal wetlands remaining to vegetated coastal wetlands, CH_4 emissions in a given year represent the cumulative area held in this category for that year and the prior 19 years.

Uncertainty

Underlying uncertainties in estimates of soil carbon removal factors, biomass change, DOM, and CH_4 emissions

[83] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed October 2023

include error in uncertainties associated with Tier 2 literature values of soil carbon removal estimates, biomass stocks, DOM, and IPCC default CH_4 emission factors, uncertainties linked to interpretation of remote sensing data, as well as assumptions that underlie the methodological approaches applied.

Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines what flux is applied. Because mean soil and biomass carbon removal for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to estimate the CH_4 flux (e.g., delineation of an 18 ppt boundary), which will need significant improvement to reduce uncertainties. The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-100 for each carbon pool and the CH_4 emissions. The combined uncertainty is 42.6 percent above and below the estimate of 0.17 MMT CO_2 Eq. In 2022, the total flux was 0.17 MMT CO_2 Eq., with lower and upper estimates of 0.10 and 0.24 MMT CO_2 Eq.

Table 6-100: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes occurring within Land Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	0.12	0.1	0.15	-20.0%	20.0%
Dead Organic Matter Flux	0.03	0.02	0.03	-25.8%	25.8%
Soil C Stock Flux	(0.14)	(0.2)	(0.1)	-17.7%	17.7%
Methane Emissions	0.17	0.12	0.22	-29.9%	29.9%
Total Uncertainty	**0.18**	**0.11**	**0.26**	**-42.2%**	**42.2%**

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal mandatory QA/QC assessment (McCombs et al. 2016). QA/QC and verification of soil carbon stock dataset has been provided by the Smithsonian Environmental Research Center and coastal wetland inventory team leads. Biomass carbon stocks are derived from peer-review literature, reviewed by U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the coastal wetland inventory team leads prior to inclusion in the *Inventory* and from IPCC reports. As a QC step, a check was undertaken confirming that coastal wetlands recognized by C-CAP represent a subset of wetlands recognized by the NRI for marine coastal states. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil carbon stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors are derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since

2016 and other relevant data that were not previously included. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increase (0.001 MMT CO_2 Eq.) for the entire time series.

Planned Improvements

Currently, the only coastal wetland conversion that is reported in the *Inventory* is lands converted to vegetated coastal wetlands. The next (1990 through 2023) *Inventory* submission is expected to include carbon stock change data for lands converted to unvegetated open water coastal wetlands.

Land Converted to Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural production of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation but would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as "reservoirs" or "other constructed waterbodies" (IPCC 2019). Reservoirs are defined as flooded land greater than 8 ha and includes the seasonally flooded land on the perimeter of permanently flooded land (i.e., inundation areas). IPCC guidance (IPCC 2019) provides default emission factors for reservoirs and several types of "other constructed waterbodies" including freshwater ponds and canals/ditches.

Land that has been flooded for 20 years or greater is defined as flooded land remaining flooded land and land flooded for less than 20 years is defined as land converted to flooded land. The distinction is based on literature reports that CO_2 and CH_4 emissions are high immediately following flooding as labile organic matter is rapidly degraded but decline to a steady background level approximately 20 years after flooding (Abril et al. 2005, Barros et al. 2011, Teodoru et al. 2012). Both CO_2 and CH_4 emissions are estimated for land converted to flooded land.

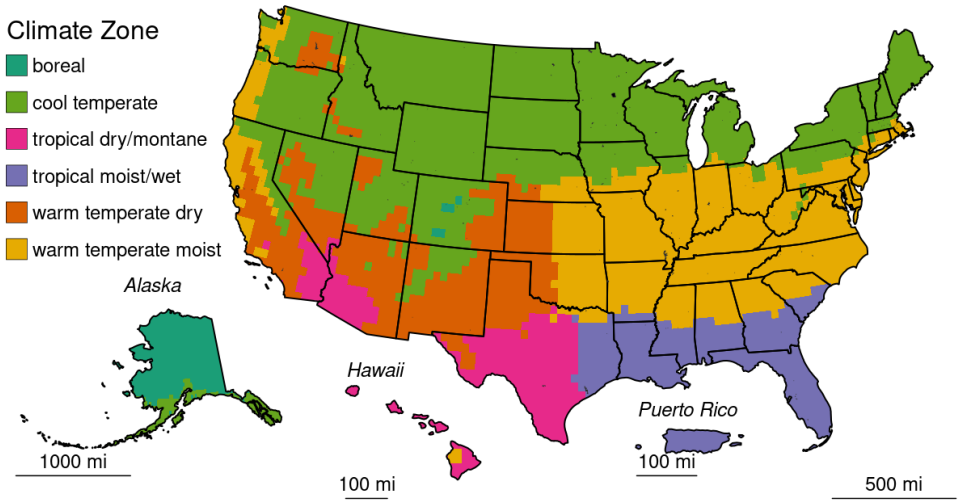
Nitrous oxide emissions from flooded lands are largely related to inputs of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. The permanently wetted portion of reservoirs are typically surrounded by periodically inundated land referred to as a "drawdown zone" or "inundation area." Greenhouse gas emissions from inundation areas are considered significant and similar per unit area to the emissions from the water surface and are therefore included in the total reservoir surface area when estimating greenhouse gas emissions from flooded land. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed flooded land (see Area Estimates below) (IPCC 2019).

In 2022, the United States and Puerto Rico contained 72,461 ha of reservoir surface area in land converted to flooded land (see Methodology and Time-Series Consistency below for calculation details) distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-17) (IPCC 2019).

Emissions from Land Converted to Flooded Land–Reservoirs

Figure 6-17: U.S. Reservoirs (black polygons) in the Land Converted to Flooded Land Category in 2022



Note: Colors represent climate zone used to derive IPCC default emission factors. Reservoirs (indicated by black polygons) are sparsely distributed across United States, but can be seen in MN, IL, and IN in this image.

Methane and CO_2 are produced in reservoirs through the natural breakdown of organic matter. Per unit area emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae). Greenhouse gases produced in reservoirs can be emitted directly from the water surface and inundation areas or as greenhouse gas-enriched water passes through the dam and the downstream river. Sufficient information exists to estimate downstream CH_4 emissions using Tier 1 IPCC guidance (IPCC 2019), but no guidance is provided for downstream CO_2 emissions. Table 6-101 and Table 6-102 below summarize nationally aggregated CH_4 and CO_2 emissions from reservoirs in land converted to flooded land. The decrease in CO_2 and CH_4 emissions through the time series is attributable to reservoirs matriculating from the land converted to flooded land category into the flooded land remaining flooded land category. Emissions have been stable since 2005, reflecting the low rate of new flooded land creation over the past 17 years.

Table 6-101: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emissions	2.5	0.4	0.2	0.2	0.2	0.2	0.2
Downstream Emissions	0.2	+	+	+	+	+	+
Total	**2.7**	**0.4**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+Indicates values less than 0.05 MMT CO_2

Note: Totals may not sum due to independent rounding.

Table 6-102: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emissions	90	14	7	7	7	7	7
Downstream Emissions	8	1	1	1	1	1	1
Total	**98**	**15**	**8**	**8**	**8**	**7**	**7**

Note: Totals may not sum due to independent rounding.

Table 6-103: CO_2 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	3.5	0.6	0.3	0.3	0.3	0.3	0.3

Table 6-104: CO_2 Emissions from Land Converted to Flooded Land—Reservoirs (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	0.9	0.2	0.1	0.1	0.1	0.1	0.1

Methane and CO_2 emissions from reservoirs in Minnesota were 8-fold greater than from any other state (Figure 6-18 and Table 6-105). This is attributed to nineteen reservoirs created in Minnesota after 2001 which impound 54,064 ha of water, 96 percent of which is located in Mille Lacs Lake.

North Dakota is the second largest source of CO_2 and CH_4 from reservoirs in land converted to flooded land. Over ninety-nine percent of land converted to flooded land reservoir surface area in North Dakota is attributed to Devils Lake. Both Mille Lacs and Devils Lakes are natural waterbodies provisioned with dams for water level management.

Figure 6-18: 2022 A) CH_4 and B) CO_2 Emissions from U.S. Reservoirs in Land Converted to Flooded Land

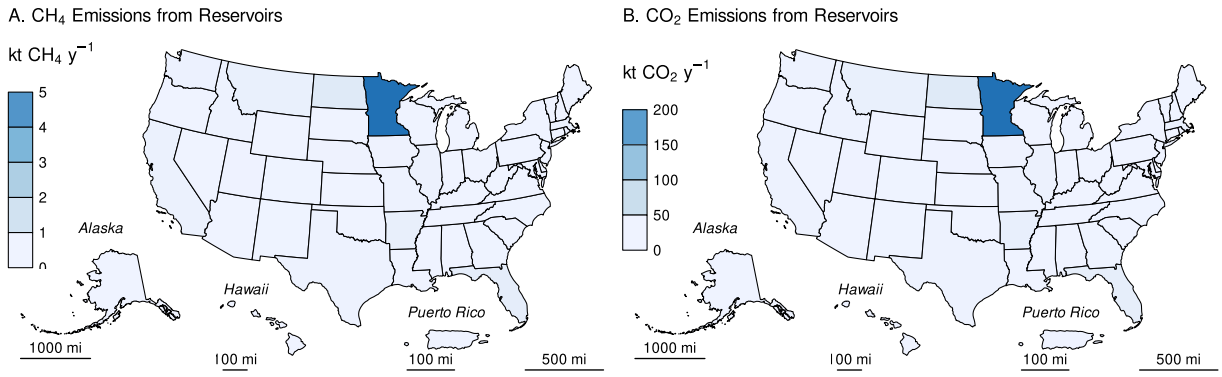


Table 6-105: Methane and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land in 2022 (kt CH_4; kt CO_2)

	CH_4			CO_2[a]
State	Surface	Downstream	Total	Surface
Alabama	0	0	0	0
Alaska	0	0	0	0
Arizona	0	0	0	0
Arkansas	+	+	+	9
California	+	+	+	3
Colorado	+	+	+	1
Connecticut	+	+	+	+
Delaware	0	0	0	0
District of Columbia	0	0	0	0
Florida	+	+	+	13
Georgia	+	+	+	1
Hawaii	0	0	0	0
Idaho	+	+	+	2

Illinois	+	+	+	4
Indiana	+	+	+	+
Iowa	+	+	+	2
Kansas	+	+	+	+
Kentucky	0	0	0	0
Louisiana	+	+	+	+
Maine	+	+	+	+
Maryland	+	+	+	+
Massachusetts	+	+	+	5
Michigan	+	+	+	+
Minnesota	5	+	5	202
Mississippi	+	+	+	+
Missouri	+	+	+	2
Montana	+	+	+	8
Nebraska	+	+	+	1
Nevada	+	+	+	+
New Hampshire	+	+	+	1
New Jersey	0	0	0	0
New Mexico	+	+	+	1
New York	+	+	+	+
North Carolina	+	+	+	1
North Dakota	+	+	1	22
Ohio	+	+	+	1
Oklahoma	0	0	0	0
Oregon	+	+	+	1
Pennsylvania	+	+	+	1
Puerto Rico	0	0	0	0
Rhode Island	0	0	0	0
South Carolina	0	0	0	0
South Dakota	+	+	+	+
Tennessee	+	+	+	1
Texas	+	+	+	3
Utah	+	+	+	1
Vermont	0	0	0	0
Virginia	0	0	0	0
Washington	+	+	+	3
West Virginia	+	+	+	+
Wisconsin	+	+	+	1
Wyoming	+	+	+	1

+ Indicates values greater than zero and less than 0.5 kt.

[a] CO_2: Only surface CO_2 emissions are included in the *Inventory.*

Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for reservoirs in land converted to flooded land follow the Tier 1 methodology in the IPCC guidance (IPCC 2019). All calculations are performed at the state level and summed to obtain national estimates. Emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-106). Downstream CH_4 emissions are calculated as 9 percent of the surface CH_4 emission (Tier 1 default). The IPCC guidance (IPCC 2019) does not address downstream CO_2 emissions, presumably because there are insufficient data in the literature to estimate this emission pathway.

The IPCC default surface emission factors are derived from model-predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zones are present in the United States.

Table 6-106: IPCC (2019) Default CH_4 and CO_2 Emission Factors for Surface Emissions from Reservoirs in Land Converted to Flooded Land

	Surface emission factor	
Climate	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Boreal	0.0277	3.45
Cool Temperate	0.0847	3.74
Warm Temperate Dry	0.1956	6.23
Warm Temperate Moist	0.1275	5.35
Tropical Dry/Montane	0.3923	10.82
Tropical Moist/Wet	0.2516	10.16

Note: Downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[84] the National Inventory of Dams (NID),[85] the National Wetlands Inventory (NWI),[86] and the Navigable Waterways (NW) network,[87] and the EPA's Safe Drinking Water Information System (SDWIS).[88] The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features greater than 8 ha in surface area are defined as reservoirs.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land–other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands

[84] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[85] See https://nid.sec.usace.army.mil.

[86] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

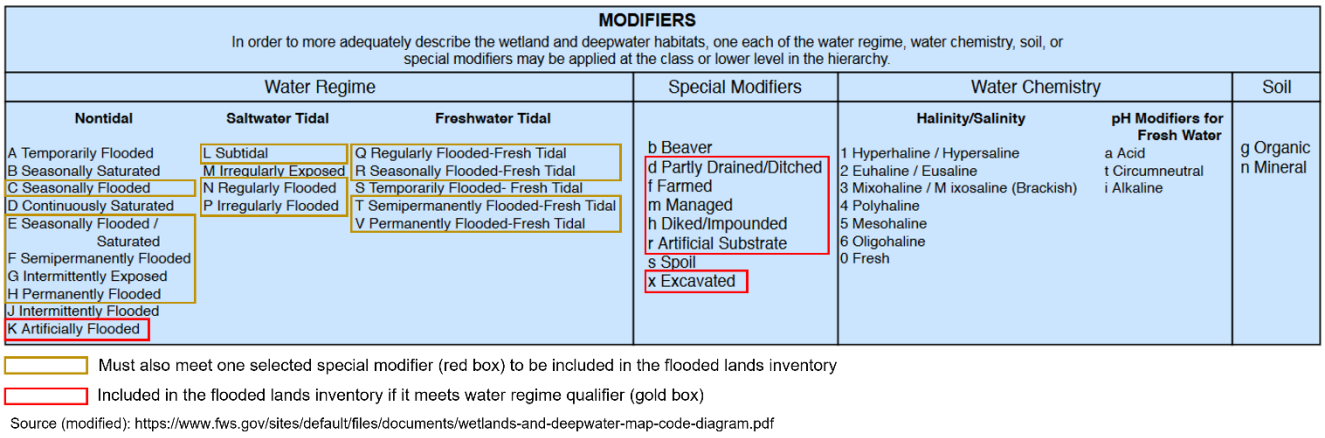
[87] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[88] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming they were created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the feature was greater than 20-years old throughout the time series. Only reservoirs less than or equal to 20-years old are included in land converted to flooded land.

Figure 6-19: Selected Features from NWI that meet Flooded Lands Criteria



IPCC (2019) allows for the exclusion of managed waterbodies from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[89]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the *Inventory*.

The surface area of reservoirs in land converted to flooded land decreased by nearly 90 percent from 1990 to 2022 (Table 6-107). This is due to reservoirs that were less than 20-years old at the beginning of time series entering the flooded land remaining flooded land category when they exceeded 20 years of age. The rate at which flooded land has aged out of the land converted to flooded land category has outpaced the rate of new dam construction. New dam construction has slowed considerably during the time series with only nine new dams constructed in 2022,[90] versus 552 in 1990 (Figure 6-20).

Table 6-107: National Totals of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

Surface Area (thousands of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	566	115	78	77	75	74	73

[89] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[90] See https://nid.sec.usace.army.mil.

Figure 6-20: Number of Dams Built per Year from 1990 through 2022

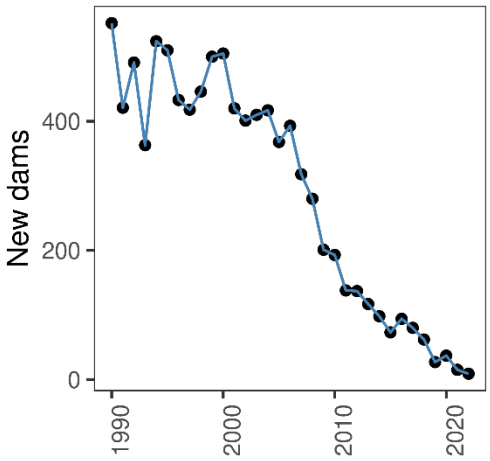


Table 6-108: State Breakdown of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	7.5	0.0	0.0	0.0	0.0	0.0	0.0
Alaska	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Arizona	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Arkansas	10.1	2.9	1.8	1.8	1.8	1.8	1.8
California	19.6	2.1	0.5	0.5	0.5	0.5	0.5
Colorado	5.9	1.3	0.3	0.3	0.3	0.3	0.3
Connecticut	2.3	2.2	0.0	0.0	0.0	0.0	0.0
Delaware	0.0	0.0	0.0	0.0	0.0	0.0	0.0
District of Columbia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	25.7	3.8	1.5	1.5	1.4	1.2	1.2
Georgia	20.6	4.9	0.1	0.1	0.1	0.1	0.1
Hawaii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Idaho	17.7	1.2	0.5	0.5	0.5	0.5	0.5
Illinois	49.2	39.4	1.4	1.3	1.3	0.8	0.8
Indiana	10.6	0.3	0.1	0.1	0.1	0.1	0.1
Iowa	12.3	3.1	1.0	1.0	0.7	0.7	0.5
Kansas	19.6	0.4	0.2	0.2	0.1	0.1	0.0
Kentucky	1.3	0.1	0.0	0.0	0.0	0.0	0.0
Louisiana	9.4	0.2	0.0	0.0	0.0	0.0	0.0
Maine	10.9	4.4	0.0	0.0	0.0	0.0	0.0
Maryland	0.8	0.1	0.1	0.1	0.1	0.1	0.1
Massachusetts	1.6	0.5	1.5	1.5	1.4	1.4	1.2
Michigan	11.6	0.9	0.1	0.1	0.1	0.1	0.1
Minnesota	9.9	6.4	54.6	54.6	54.3	54.2	54.1
Mississippi	6.2	0.6	0.1	0.1	0.1	0.1	0.1
Missouri	16.4	0.5	0.4	0.4	0.4	0.4	0.4
Montana	14.4	3.9	2.1	2.1	2.1	2.1	2.1
Nebraska	5.8	1.7	0.6	0.6	0.3	0.3	0.3
Nevada	1.6	1.1	0.1	0.1	0.1	0.1	0.1
New Hampshire	0.4	0.2	0.1	0.1	0.1	0.1	0.1
New Jersey	0.7	0.6	0.0	0.0	0.0	0.0	0.0
New Mexico	1.3	0.1	0.1	0.1	0.1	0.1	0.1
New York	4.2	2.6	0.1	0.1	0.1	0.1	0.1

North Carolina	19.7	0.7	0.3	0.2	0.2	0.2	0.2
North Dakota	7.5	3.5	6.3	6.3	6.3	6.2	5.9
Ohio	7.2	1.3	0.3	0.3	0.2	0.2	0.1
Oklahoma	28.7	0.2	0.0	0.0	0.0	0.0	0.0
Oregon	6.2	0.4	0.2	0.2	0.2	0.1	0.1
Pennsylvania	12.6	1.3	0.1	0.1	0.1	0.1	0.1
Puerto Rico	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rhode Island	0.1	0.0	0.0	0.0	0.0	0.0	0.0
South Carolina	18.5	5.8	0.0	0.0	0.0	0.0	0.0
South Dakota	0.5	3.9	0.8	0.8	0.0	0.0	0.0
Tennessee	58.7	0.0	0.1	0.1	0.1	0.1	0.1
Texas	74.8	0.9	0.3	0.3	0.2	0.2	0.2
Utah	1.9	0.1	0.3	0.3	0.3	0.3	0.3
Vermont	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Virginia	5.8	0.4	0.0	0.0	0.0	0.0	0.0
Washington	5.3	1.6	0.9	0.9	0.5	0.5	0.5
West Virginia	3.1	1.6	0.1	0.0	0.0	0.0	0.0
Wisconsin	1.9	0.4	0.2	0.2	0.2	0.2	0.2
Wyoming	15.1	6.5	0.4	0.2	0.2	0.2	0.2
Total	**565.8**	**114.6**	**77.6**	**77.1**	**74.7**	**73.7**	**72.5**

Uncertainty

Uncertainty in estimates of CH_4 and CO_2 emissions from reservoirs on land converted to flooded land were developed using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory (Table 1-105). Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-109: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	0.19	0.17	0.21	-11.5%	+11.9%
Surface	CO_2	0.2	0.26	0.33	-11.7%	+12.4%
Downstream	CH_4	+	+	0.08	-54.1%	+397.0%
Total		**0.5**	**0.44**	**0.59**	**-12.2%**	**+18.8%**

+ Indicates values less than 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation

Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current 1990 through 2022 *Inventory* has major updates for MS, ND, NM, and MT.

Overall, the recalculations resulted in substantial increases in methane and carbon dioxide emissions in the first few years of the time series (e.g., increase of 3.8 MMT CO_2 Eq. in 1990), but the differences were minor by 2008 through 2021 (<0.1 MMT CO_2 Eq.).

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[91] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

Emissions from Land Converted to Flooded Land–Other Constructed Waterbodies

Freshwater ponds are the only type of flooded lands within the "other constructed waterbodies" subcategory of land converted to flooded land that are included in this *Inventory* (see Methodology for details) because age data are not available for canals and ditches. All canals and ditches are assumed to be greater than 20-years old throughout the time series and are included in flooded land remaining flooded land.

IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." The IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) elaborates on this description by defining waterbodies less than 8 ha as a subset of "other constructed waterbodies." For this *Inventory*, ponds are defined as managed flooded land not identified as "canal/ditch" (see Methods below) with

[91] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

surface area less than 8 ha. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emission rates than the latter. Activity data on pond salinity is not uniformly available for the United States and all ponds in land converted to flooded land are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are sites of substantial CH_4 and CO_2 emissions from anaerobic sediments.

Methane and CO_2 emissions from freshwater ponds decreased 95 percent from 1990 to 2022 due to flooded land matriculating from land converted to flooded land to flooded land remaining flooded land. In 2022, states in the Great Plains region generally had the greatest CO_2 and CH_4 emissions from freshwater ponds in land converted to flooded land (Table 6-110 through Table 6-114, Figure 6-21). Mississippi had the second greatest emissions of all states, partly due to the relatively high CO_2 emission factor for the tropical moist/wet climate zone (Figure 6-17, Table 6-115).

Table 6-110: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT CO_2 Eq.

Table 6-111: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	5	1	+	+	+	+	+

+ Indicates values less than 0.5 kt.

Table 6-112: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	+	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT C.

Table 6-113: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.04	0.01	+	+	+	+	+

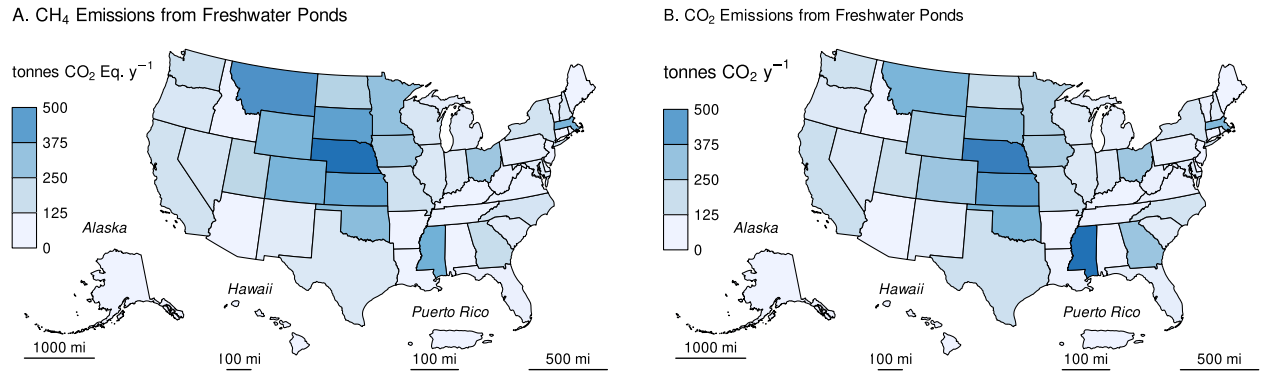
+ Indicates values less than 0.005 MMT C.

Table 6-114: CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land in 2022 (MT CO_2 Eq.)

	Freshwater Ponds		
State	CH_4	CO_2	Total
Alabama	0	0	0
Alaska	0	0	0
Arizona	0	0	0
Arkansas	1	1	3
California	126	146	272
Colorado	382	290	672
Connecticut	0	0	0
Delaware	0	0	1
District of Columbia	0	0	0
Florida	18	37	55
Georgia	164	293	457

Hawaii	0	0	0
Idaho	0	0	0
Illinois	83	74	157
Indiana	66	69	135
Iowa	282	254	535
Kansas	435	456	891
Kentucky	3	3	5
Louisiana	3	6	10
Maine	1	1	2
Maryland	58	60	118
Massachusetts	381	358	738
Michigan	41	30	71
Minnesota	317	232	549
Mississippi	400	612	1,012
Missouri	133	139	271
Montana	509	371	880
Nebraska	620	567	1,186
Nevada	103	80	183
New Hampshire	80	59	139
New Jersey	0	0	0
New Mexico	57	46	103
New York	120	96	215
North Carolina	107	112	219
North Dakota	229	167	396
Ohio	289	285	574
Oklahoma	339	378	717
Oregon	89	71	161
Pennsylvania	29	25	54
Puerto Rico	0	0	0
Rhode Island	0	0	0
South Carolina	47	49	95
South Dakota	455	332	788
Tennessee	11	11	22
Texas	83	138	222
Utah	207	151	359
Vermont	15	11	26
Virginia	10	11	21
Washington	140	132	272
West Virginia	19	19	38
Wisconsin	93	68	162
Wyoming	369	269	639
Total	**6,917**	**6,510**	**13,427**

Figure 6-21: 2022 A) CH_4 and B) CO_2 Emissions from Other Constructed Waterbodies (Freshwater Ponds) in Land Converted to Flooded Land (MT CO_2 Eq.)



Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for other constructed waterbodies in land converted to flooded land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Greenhouse gas emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-115). Due to a lack of empirical data on CO_2 emissions from recently created ponds, IPCC (2019) states "For all types of ponds created by damming, the methodology described above to estimate CO_2 emissions from land converted to reservoirs may be used." This *Inventory* uses IPCC default CO_2 emission factors for land converted to reservoirs when estimating CO_2 emissions from land converted to freshwater ponds. IPCC guidance also states that "there is insufficient information available to derive separate CH_4 emission factors for recently constructed ponds…" and allows for the use of IPCC default CH_4 emission factors for land remaining flooded land. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-115: IPCC Default Methane and CO_2 Emission Factors for Other Constructed Waterbodies in Land Converted to Flooded Land

		Emission Factor	
Other Constructed Waterbody	**Climate Zone**	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Freshwater ponds	Boreal	0.183	3.45
Freshwater ponds	Cool Temperate	0.183	3.74
Freshwater ponds	Warm Temperate Dry	0.183	6.23
Freshwater ponds	Warm Temperate Moist	0.183	5.35
Freshwater ponds	Tropical Dry/Montane	0.183	10.82
Freshwater ponds	Tropical Moist/Wet	0.183	10.16

Area Estimates

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[92] the National Inventory of Dams (NID),[93] the National Wetlands Inventory (NWI),[94] and the Navigable Waterways (NW) network[95], and the EPA's Safe Drinking Water Information System (SDWIS)[96]. The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed". The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 1,350 ha of freshwater ponds in land converted to flooded land. The surface area of freshwater ponds decreased by 95 percent from 1990 to 2022 due to flooded lands aging out of land converted to flooded land more quickly than new flooded lands entered the category. The greatest reduction in freshwater pond surface area occurred in Iowa, Kansas, and Georgia (Table 6-117). Freshwater ponds in the 2021 inventory are most abundant in Nebraska, Montana, and Kansas (Figure 6-22).

---

[92] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[93] See https://nid.sec.usace.army.mil.

[94] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[95] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[96] Not publicly available due to security concerns.

Table 6-116: National Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

Other Constructed Waterbodies	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	25,492	5,357	2,604	2,317	1,983	1,673	1,472

Figure 6-22: Surface Area of Other Constructed Waterbodies in Land Converted to Flooded Land (ha) in 2022

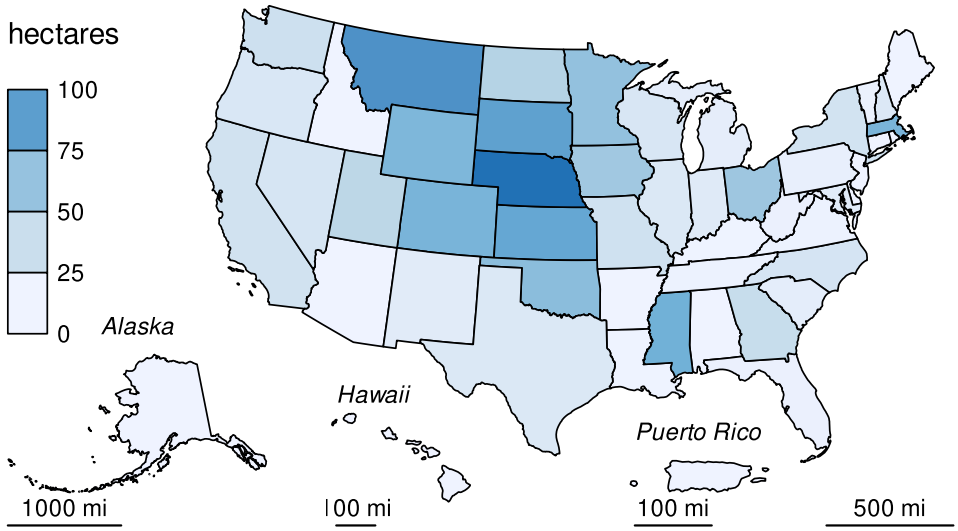


Table 6-117: State Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	317	13	0	0	0	0	0
Alaska	3	0	0	0	0	0	0
Arizona	39	16	4	4	0	0	0
Arkansas	331	0	0	0	0	0	0
California	263	103	45	40	33	31	25
Colorado	279	71	79	78	89	89	75
Connecticut	67	2	0	0	0	0	0
Delaware	4	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0
Florida	154	58	15	10	10	4	4
Georgia	1,686	83	35	32	32	32	32
Hawaii	11	4	0	0	0	0	0
Idaho	133	8	1	1	1	0	0
Illinois	557	133	42	37	27	26	16
Indiana	494	133	28	23	23	23	13
Iowa	2,592	1,580	474	290	172	76	55
Kansas	2,099	147	113	104	103	87	85
Kentucky	394	30	1	1	1	1	1
Louisiana	130	17	7	7	1	1	1
Maine	51	10	0	0	0	0	0
Maryland	226	81	20	20	18	15	11

Massachusetts	68	79	93	86	80	78	74
Michigan	162	37	16	16	8	8	8
Minnesota	344	142	103	101	79	71	62
Mississippi	414	200	124	117	98	85	78
Missouri	3,451	104	38	34	32	29	26
Montana	400	109	105	100	99	99	99
Nebraska	1,427	374	182	164	133	125	121
Nevada	21	64	26	26	22	22	20
New Hampshire	154	61	17	17	16	16	16
New Jersey	50	21	0	0	0	0	0
New Mexico	14	14	19	17	17	17	11
New York	312	124	31	29	29	24	23
North Carolina	498	92	28	28	25	22	21
North Dakota	90	135	67	61	51	48	45
Ohio	431	293	121	107	75	60	56
Oklahoma	2,008	147	111	95	81	75	66
Oregon	220	69	25	22	18	17	17
Pennsylvania	255	33	6	6	6	6	6
Puerto Rico	0	0	0	0	0	0	0
Rhode Island	9	7	0	0	0	0	0
South Carolina	826	230	22	13	9	9	9
South Dakota	227	98	105	94	93	89	89
Tennessee	389	37	14	9	2	2	2
Texas	2,950	89	21	16	17	16	16
Utah	68	19	42	42	40	40	40
Vermont	70	11	3	3	3	3	3
Virginia	58	4	2	2	2	2	2
Washington	153	57	31	31	28	27	27
West Virginia	130	10	4	4	4	4	4
Wisconsin	146	21	18	18	18	18	18
Wyoming	316	190	79	79	78	75	72
Total	**25,492**	**5,357**	**2,317**	**1,983**	**1,673**	**1,472**	**1,350**

Uncertainty

Uncertainty in estimates of CO_2 and CH_4 emissions from land converted to flooded land–other constructed water bodies include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in the NHD, NWI, NID, and NW are unknown, but uncertainty for remote sensing products is ±10 to 15 percent (IPCC 2003). EPA assumes an uncertainty of ± 15 percent for the flooded land area inventory based on expert judgment. These uncertainties do not include the underestimate of pond surface area discussed above.

Table 6-118: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land

Source	Gas	2022 Emission Estimate (kt CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (kt CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Freshwater ponds	CH_4	6.90	6.80	7.10	-2.3%	+2.7%
Freshwater ponds	CO_2	6.51	6.38	6.62	-2.0%	+1.8%
Total		**13.42**	**13.18**	**13.70**	**-1.8%**	**+2.1%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS with collaboration from many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory. Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory.* The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for “year of dam completion” for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 and CO_2 emissions from other constructed waterbodies of 0.03 MMT CO_2 Eq., or 51 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Features < 8 ha in the NW that were not identified as canal/ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (i.e., 1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.10 Settlements Remaining Settlements (CRT Category 4E1)

Soil Carbon Stock Changes (CRT Category 4E1)

Soil organic C stock changes for settlements remaining settlements occur in both mineral and organic soils. However, the United States does not estimate changes in soil organic C stocks for mineral soils in settlements remaining settlements. This approach is consistent with the assumption of the Tier 1 method in the 2006 *IPCC Guidelines* (IPCC 2006) that inputs equal outputs, and therefore the soil organic C stocks do not change in this land use category. This assumption may be re-evaluated in the future if funding and resources are available to conduct an analysis of soil organic C stock changes for mineral soils in settlements remaining settlements.

Drainage of organic soils is common when wetland areas have been developed for settlements. Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic carbon by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. Drainage of organic soils leads to aeration of the soil that accelerates decomposition rate and CO_2 emissions.[97] Due to the depth and richness of the organic layers, carbon loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986).

Settlements remaining settlements includes all areas that have been settlements for a continuous time period of at least 20 years according to the 2017 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2020)[98] or according to the National Land Cover Dataset (NLCD) for federal lands (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for settlements remaining settlements. Specifically, Alaska and the small amount of settlements on federal lands are not included in this *Inventory* even though these areas are part of the U.S. managed land base. There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future *Inventory* (see Planned Improvements section).

CO_2 emissions from drained organic soils in settlements are 15.4 MMT CO_2 Eq. (4.2 MMT C) in 2022 (see Table 6-119 and Table 6-120). Although the flux is relatively small, the amount has increased by 56 percent since 1990 due to an increase in area of drained organic soils in settlements.

Table 6-119: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	9.9	10.1	14.4	14.6	15.1	15.4	15.4

[97] N_2O emissions from drained organic soils are included in the N_2O Emissions from Settlement Soils section.

[98] NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of Settlements Remaining Settlements in the early part of the time series to the extent that some areas are converted to settlements between 1971 and 1978.

Table 6-120: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	2.7	2.7	3.9	4.0	4.1	4.2	4.2

Methodology and Time-Series Consistency

An IPCC Tier 2 method is used to estimate soil organic C stock changes for organic soils in settlements remaining settlements (IPCC 2006). Organic soils in settlements remaining settlements are assumed to be losing C at a rate similar to croplands due to deep drainage, and therefore emission rates are based on country-specific values for cropland (Ogle et al. 2003).

The land area designated as settlements is based primarily on the 2017 NRI (USDA-NRCS 2020) with additional information from the NLCD to the extend the time series through 2020 (Yang et al. 2018). Soils are classified as organic using data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-121). The area of land on organic soils in settlements remaining settlements has increased from 216 thousand hectares in 1990 to over 327 thousand hectares in 2020.

Table 6-121: Thousands of Hectares of Drained Organic Soils in Settlements Remaining Settlements

	1990	2005	2014	2015	2016	2017	2018	2019	2020	2021	2022
Area (Thousand Hectares)	216	219	276	283	291	302	311	317	327	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

To estimate CO_2 emissions from drained organic soils across the time series from 1990 to 2020, the area of organic soils by climate (i.e., cool temperate, warm temperate, subtropical) in settlements remaining settlements is multiplied by the appropriate country-specific emission factors for cropland remaining cropland under the assumption that there is deep drainage of the soils. The emission factors are 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions, and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2020 time series (see Box 6-4 in cropland remaining cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied in future inventories to recalculate the estimates beyond 2020 as new activity data are integrated into the analysis.

Uncertainty

The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was

incorporated into the analysis for the latter part of the time series. Soil carbon losses from drained organic soils in settlements remaining settlements for 2022 are estimated to be between 7.7 and 23.2 MMT CO_2 Eq. at a 95 percent confidence level (Table 6-115). This indicates a range of 50 percent below and 50 percent above the 2022 emission estimate of 15.4 MMT CO_2 Eq.

Table 6-122: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
		(MMT CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soils	CO_2	15.4	7.7	23.2	-50%	+50%

[a] Range of emission estimates is a 95 percent confidence interval.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this *Inventory*.

Recalculations Discussion

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, and update that was made by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using NLCD. As a result of this change, CO_2-equivalent emissions changed annually with an average annual decrease of 1.8 MMT CO_2 Eq., or 14 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key improvement is to estimate CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands. This improvement will resolve most of the differences between the managed land base for settlements remaining settlements and amount of area currently included in this *Inventory* as settlements remaining settlements (see Table 6-123). This improvement will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-123: Area of Managed Land in Settlements Remaining Settlements that is not included in the current *Inventory* (Thousand Hectares)

Year	Area (Thousand Hectares)		
	SRS Managed Land Area (Section 6.1)	SRS Area Included in Inventory	Difference
1990	30,548	30,366	182
1991	30,545	30,364	182
1992	30,543	30,361	182
1993	30,470	30,288	182
1994	30,385	30,203	182
1995	30,322	30,141	182
1996	30,263	30,081	182
1997	30,193	30,011	182
1998	30,127	29,945	182
1999	30,073	29,891	182
2000	30,015	29,834	182
2001	29,963	29,781	182
2002	29,956	29,774	182
2003	30,479	30,298	182
2004	30,973	30,791	182
2005	31,432	31,250	182
2006	31,940	31,758	182
2007	32,397	32,215	182
2008	33,015	32,833	182
2009	33,591	33,410	182
2010	34,166	33,984	182
2011	34,731	34,549	182
2012	35,302	35,120	182
2013	36,224	36,042	182
2014	37,159	36,977	182
2015	38,026	37,844	182
2016	38,938	38,756	182
2017	39,861	39,679	182
2018	40,756	40,574	182
2019	41,602	41,420	182
2020	42,452	42,270	182
2021	43,175	*	*
2022	43,734	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

Changes in Carbon Stocks in Settlement Trees (CRT Category 4E1)

Settlements are land uses where human populations and activities are concentrated. In these areas, the anthropogenic impacts on tree growth, stocking and mortality are particularly pronounced (Nowak 2012) in comparison to forest lands where non-anthropogenic forces can have more significant impacts. Estimates included in this section include net CO_2 and carbon flux from trees on settlements remaining settlements and land converted to settlements as it is not possible to report on these separately at this time.

Trees in settlement areas of the United States are estimated to account for an average annual net sequestration of 118.2 MMT CO_2 Eq. (32.2 MMT C) over the period from 1990 through 2022. Net carbon sequestration from settlement trees in 2022 is estimated to be 138.5 MMT CO_2 Eq. (37.8 MMT C) (Table 6-124). Dominant factors affecting carbon flux trends for settlement trees are changes in the amount of settlement area (increasing

sequestration due to more land and trees) and net changes in tree cover (e.g., tree losses versus tree gains through planting and natural regeneration), with percent tree cover trending downward recently. In addition, changes in species composition, tree sizes and tree densities affect base carbon flux estimates. Annual sequestration increased by 43 percent between 1990 and 2022 due to increases in settlement area and changes in total tree cover.

Trees in settlements often grow faster than forest trees because of their relatively open structure (Nowak and Crane 2002). Because tree density in settlements is typically much lower than in forested areas, the carbon storage per hectare of land is in fact smaller for settlement areas than for forest areas. Also, percent tree cover in settlement areas is less than in forests and this urban tree cover varies significantly across the United States (e.g., Nowak and Greenfield 2018a). To quantify the carbon stored in settlement trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for forest lands).

Table 6-124: Net Flux from Trees in Settlements Remaining Settlements (MMT CO_2 Eq. and MMT C)[a]

Year	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
MMT C	(26.3)	(31.9)	(36.7)	(37.0)	(37.3)	(37.6)	(37.8)

[a] These estimates include net CO_2 and C flux from trees on settlements remaining settlements and land converted to settlements as it is not possible to report on these separately at this time.

Note: Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

To estimate net carbon sequestration in settlement areas, three types of data are required for each state:

1. Settlement area
2. Percent tree cover in settlement areas
3. Carbon sequestration density per unit of tree cover

Settlement Area

Settlement area is defined in Section 6.1 as a land-use category representing developed areas. The data used to estimate settlement area within Section 6.1 comes from the latest NRI as updated through 2017, with the extension of the time series through 2022 based on assuming the settlement area is the same as 2017. The NRI data is also harmonized with the FIA dataset, which is available through 2022, and the 2019 NLCD dataset. This process of combining the datasets extends the time series to ensure that there is a complete and consistent representation of land use data for all source categories in the LULUCF sector. Annual estimates of the net CO_2 flux (Table 6-124) were developed based on estimates of annual settlement area and tree cover derived from NLCD developed lands. Developed land, which was used to estimate tree cover in settlement areas, is about six percent higher than the area categorized as settlements in the representation of the U.S. land base developed for this report.

Percent Tree Cover in Settlement Areas

Percent tree cover in settlement area by state is needed to convert settlement land area to settlement tree cover area. Converting to tree cover area is essential as tree cover, and thus carbon estimates, can vary widely among states in settlement areas due to variations in the amount of tree cover (e.g., Nowak and Greenfield 2018a). However, since the specific geography of settlement area is unknown because they are based on NRI sampling methods, NLCD developed land was used to estimate the percent tree cover to be used in settlement areas. The NLCD developed land cover classes 21-24 (developed, open space (21), low intensity (22), medium intensity (23), and high intensity (24)) were used to estimate percent tree cover in settlement area by state (U.S. Department of Interior 2018; MRLC 2013).

a) "Developed, Open Space – areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes." Plots designated as either park, recreation, cemetery, open space, institutional or vacant land were classified as "Developed, Open Space".

b) "Developed, Low Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family housing units." Plots designated as single family or low-density residential land were classified as "Developed, Low Intensity".

c) "Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 to 79 percent of the total cover. These areas most commonly include single-family housing units." Plots designated as medium density residential, other urban or mixed urban were classified as "Developed, Medium Intensity".

d) "Developed High Intensity – highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover." Plots designated as either commercial, industrial, high density residential, downtown, multi-family residential, shopping, transportation or utility were classified as "Developed, High Intensity".

As NLCD is known to underestimate tree cover (Nowak and Greenfield 2010), photo-interpretation of tree cover within NLCD developed lands was conducted for the years of c. 2016 and 2020 using 1,000 random points to determine an average adjustment factor for NLCD tree cover estimates in developed land and determine recent tree cover changes. This photo-interpretation of change followed methods detailed in Nowak and Greenfield (2018b). Percent tree cover (%TC) in settlement areas by state was estimated as:

%TC in state = state NLCD %TC x national photo-interpreted %TC / national NLCD %TC

Percent tree cover in settlement areas by year was set as follows:

- 1990 to 2011: used 2011 NLCD tree cover adjusted with 2011 photo-interpreted values
- 2012 to 2015: used 2011 NLCD tree cover adjusted with photo-interpreted values, which were interpolated from values between 2011 and 2016
- 2016 to 2020: used 2016 NLCD tree cover adjusted with 2020 photo-interpreted values

Carbon Sequestration Density per Unit of Tree Cover

Methods for quantifying settlement tree biomass, carbon sequestration, and carbon emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, net carbon sequestration estimates followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and urban areas within entire states were used to estimate carbon in tree biomass from field data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, crown competition, and growing season to generate estimates of gross carbon sequestration in settlement trees for all 50 states and the District of Columbia. Third, estimates of carbon emissions due to mortality and decomposition were subtracted from gross carbon sequestration estimates to obtain estimates of net carbon sequestration. Carbon storage, gross and net sequestration estimates were standardized per unit tree cover based on tree cover in the study area.

Settlement tree carbon estimates are based on published literature (Nowak et al. 2013; Nowak and Crane 2002; Nowak 1994) as well as newer data from the i-Tree database[99] and U.S. Forest Service urban forest inventory data (e.g., Nowak et al. 2016, 2017) (Table 6-125). These data are based on collected field measurements in several U.S. cities between 1989 and 2017. Carbon storage and sequestration in these cities were estimated using the U.S. Forest Service's i-Tree Eco model (Nowak et al. 2008). This computer model uses standardized field data from randomly located plots, along with local hourly air pollution and meteorological data, to quantify urban forest structure, monetary values of the urban forest, and environmental effects, including total carbon stored and annual carbon sequestration (Nowak et al. 2013).

In each city, a random sample of plots were measured to assess tree stem diameter, tree height, crown height and crown width, tree location, species, and canopy condition. The data for each tree were used to estimate total dry-weight biomass using allometric models, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, and wood moisture content. Total dry weight biomass was converted to carbon by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for settlement trees having less aboveground biomass for a given stem diameter than predicted by allometric models based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only carbon stored in wood. Estimated carbon storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover.

Table 6-125: Carbon Storage (kg C/m² tree cover), Gross and Net Sequestration (kg C/m² tree cover/year) and Tree Cover (percent) among Sampled U.S. Cities (see Nowak et al. 2013)

			Sequestration						
City	Storage	SE	Gross	SE	Net	SE	Ratio[a]	Tree Cover	SE
Adrian, MI	12.17	1.88	0.34	0.04	0.13	0.07	0.36	22.1	2.3
Albuquerque, NM	5.61	0.97	0.24	0.03	0.20	0.03	0.82	13.3	1.5
Arlington, TX	6.37	0.73	0.29	0.03	0.26	0.03	0.91	22.5	0.3
Atlanta, GA	6.63	0.54	0.23	0.02	0.18	0.03	0.76	53.9	1.6
Austin, TX	3.57	0.25	0.17	0.01	0.13	0.01	0.73	30.8	1.1
Baltimore, MD	10.30	1.24	0.33	0.04	0.20	0.04	0.59	28.5	1.0
Boise, ID	7.33	2.16	0.26	0.04	0.16	0.06	0.64	7.8	0.2
Boston, MA	7.02	0.96	0.23	0.03	0.17	0.02	0.73	28.9	1.5
Camden, NJ	11.04	6.78	0.32	0.20	0.03	0.10	0.11	16.3	9.9
Casper, WY	6.97	1.50	0.22	0.04	0.12	0.04	0.54	8.9	1.0
Chester, PA	8.83	1.20	0.39	0.04	0.25	0.05	0.64	20.5	1.7
Chicago (region), IL	9.38	0.59	0.38	0.02	0.26	0.02	0.70	15.5	0.3
Chicago, IL	6.03	0.64	0.21	0.02	0.15	0.02	0.70	18.0	1.2
Corvallis, OR	10.68	1.80	0.22	0.03	0.20	0.03	0.91	32.6	4.1
El Paso, TX	3.93	0.86	0.32	0.05	0.23	0.05	0.72	5.9	1.0
Freehold, NJ	11.50	1.78	0.31	0.05	0.20	0.05	0.64	31.2	3.3
Gainesville, FL	6.33	0.99	0.22	0.03	0.16	0.03	0.73	50.6	3.1
Golden, CO	5.88	1.33	0.23	0.05	0.18	0.04	0.79	11.4	1.5
Grand Rapids, MI	9.36	1.36	0.30	0.04	0.20	0.05	0.65	23.8	2.0
Hartford, CT	10.89	1.62	0.33	0.05	0.19	0.05	0.57	26.2	2.0
Houston, TX	4.55	0.48	0.31	0.03	0.25	0.03	0.83	18.4	1.0
Indiana[b]	8.80	2.68	0.29	0.08	0.27	0.07	0.92	20.1	3.2
Jersey City, NJ	4.37	0.88	0.18	0.03	0.13	0.04	0.72	11.5	1.7
Kansas[b]	7.42	1.30	0.28	0.05	0.22	0.04	0.78	14.0	1.6
Kansas City (region), MO/KS	7.79	0.85	0.39	0.04	0.26	0.04	0.67	20.2	1.7

[99] See http://www.itreetools.org.

Lake Forest Park, WA	12.76	2.63	0.49	0.07	0.42	0.07	0.87	42.4	0.8
Las Cruces, NM	3.01	0.95	0.31	0.14	0.26	0.14	0.86	2.9	1.0
Lincoln, NE	10.64	1.74	0.41	0.06	0.35	0.06	0.86	14.4	1.6
Los Angeles, CA	4.59	0.51	0.18	0.02	0.11	0.02	0.61	20.6	1.3
Milwaukee, WI	7.26	1.18	0.26	0.03	0.18	0.03	0.68	21.6	1.6
Minneapolis, MN	4.41	0.74	0.16	0.02	0.08	0.05	0.52	34.1	1.6
Moorestown, NJ	9.95	0.93	0.32	0.03	0.24	0.03	0.75	28.0	1.6
Morgantown, WV	9.52	1.16	0.30	0.04	0.23	0.03	0.78	39.6	2.2
Nebraska[b]	6.67	1.86	0.27	0.07	0.23	0.06	0.84	15.0	3.6
New York, NY	6.32	0.75	0.33	0.03	0.25	0.03	0.76	20.9	1.3
North Dakota[b]	7.78	2.47	0.28	0.08	0.13	0.08	0.48	2.7	0.6
Oakland, CA	5.24	0.19	NA	NA	NA	NA	NA	21.0	0.2
Oconomowoc, WI	10.34	4.53	0.25	0.10	0.16	0.06	0.65	25.0	7.9
Omaha, NE	14.14	2.29	0.51	0.08	0.40	0.07	0.78	14.8	1.6
Philadelphia, PA	8.65	1.46	0.33	0.05	0.29	0.05	0.86	20.8	1.8
Phoenix, AZ	3.42	0.50	0.38	0.04	0.35	0.04	0.94	9.9	1.2
Roanoke, VA	9.20	1.33	0.40	0.06	0.27	0.05	0.67	31.7	3.3
Sacramento, CA	7.82	1.57	0.38	0.06	0.33	0.06	0.87	13.2	1.7
San Francisco, CA	9.18	2.25	0.24	0.05	0.22	0.05	0.92	16.0	2.6
Scranton, PA	9.24	1.28	0.40	0.05	0.30	0.04	0.74	22.0	1.9
Seattle, WA	9.59	0.98	0.67	0.06	0.55	0.05	0.82	27.1	0.4
South Dakota[b]	3.14	0.66	0.13	0.03	0.11	0.02	0.87	16.5	2.2
Syracuse, NY	9.48	1.08	0.30	0.03	0.22	0.04	0.72	26.9	1.3
Tennessee[b]	6.47	0.50	0.34	0.02	0.30	0.02	0.89	37.7	0.8
Washington, DC	8.52	1.04	0.26	0.03	0.21	0.03	0.79	35.0	2.0
Woodbridge, NJ	8.19	0.82	0.29	0.03	0.21	0.03	0.73	29.5	1.7

SE (Standard Error)
NA (Not Available)
[a] Ratio of net to gross sequestration
[b] Statewide assessment of urban areas

To determine gross sequestration rates, tree growth rates need to be estimated. Base growth rates were standardized for open-grown trees in areas with 153 days of frost-free length based on measured data on tree growth (Nowak et al. 2013). These growth rates were adjusted to local tree conditions based on length of frost-free season, crown competition (as crown competition increased, growth rates decreased), and tree condition (as tree condition decreased, growth rates decreased). Annual growth rates were applied to each sampled tree to estimate gross annual sequestration–that is, the difference in carbon storage estimates between year 1 and year (x + 1) represents the gross amount of carbon sequestered. These annual gross carbon sequestration rates for each tree were then scaled up to city estimates using tree population information. Total carbon sequestration was divided by total tree cover to estimate a gross carbon sequestration density (kg C/m^2 of tree cover/year). The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates.

Where gross carbon sequestration accounts for all carbon sequestered, net carbon sequestration for settlement trees considers carbon emissions associated with tree death and removals. The third step in the methodology estimates net carbon emissions from settlement trees based on estimates of annual mortality, tree condition, and assumptions about whether dead trees were removed from the site. Estimates of annual mortality rates by diameter class and condition class were obtained from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass (Nowak et al. 2002). The estimated annual gross carbon emission rates for each plot were then scaled up to city estimates using tree population information.

The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric models applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric model could be found

for the particular species, the average result for the genus or botanical relative was used. The adjustment (0.8) to account for less live tree biomass in open-grown urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost-free days divided by 153. Growth rates were then adjusted for CLE. The CLE-adjusted growth rate was then adjusted based on tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-126) were compiled in units of carbon sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state settlement area and developed land percent tree cover data to calculate each state's annual net carbon sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate developed land percent tree cover data.

Net annual carbon sequestration estimates were obtained for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.73, the average ratio for net/gross sequestration (Table 6-126). However, state specific ratios were used where available.

State Carbon Sequestration Estimates

The gross and net annual carbon sequestration values for each state were multiplied by each state's settlement area of tree cover, which was the product of the state's settlement area and the state's tree cover percentage based on NLCD developed land. The model used to calculate the total carbon sequestration amounts for each state, can be written as follows:

Equation 6-1: Net State Annual Carbon Sequestration

$$\text{Net state annual C sequestration (t C/yr)} = \text{Gross state sequestration rate (t C/ha/yr)} \times \text{Net to Gross state sequestration ratio} \times \text{state settlement Area (ha)} \times \%\ \text{state tree cover in settlement area}$$

The results for all 50 states and the District of Columbia are given in Table 6-126. This approach is consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in carbon stocks in the living biomass of settlement trees. Instead, the methodology applied here uses estimates of net carbon sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

Table 6-126: Estimated Annual Carbon Sequestration, Tree Cover, and Annual Carbon Sequestration per Area of Tree Cover for settlement areas in the United States by State and the District of Columbia (2022)

State	Gross Annual Sequestration (Metric Tons C/Year)	Net Annual Sequestration (Metric Tons C/Year)	Tree Cover (Percent)	Gross Annual Sequestration per Area of Tree Cover (kg C/m²/Year)	Net Annual Sequestration per Area of Tree Cover (kg C/m²/Year)	Net: Gross Annual Sequestration Ratio
Alabama	2,268,736	1,653,170	53.1	0.376	0.274	0.73
Alaska	150,345	109,553	47.0	0.169	0.123	0.73

Arizona	165,494	120,591	4.5	0.388	0.283	0.73
Arkansas	1,316,764	959,492	48.5	0.362	0.264	0.73
California	2,015,461	1,468,615	16.8	0.426	0.311	0.73
Colorado	142,538	103,864	7.9	0.216	0.157	0.73
Connecticut	649,817	473,505	58.2	0.262	0.191	0.73
Delaware	101,819	74,193	24.2	0.366	0.267	0.73
DC	12,919	9,414	24.9	0.366	0.267	0.73
Florida	4,632,104	3,375,296	39.9	0.520	0.379	0.73
Georgia	3,886,939	2,832,313	55.9	0.387	0.282	0.73
Hawaii	302,023	220,076	41.4	0.637	0.464	0.73
Idaho	59,771	43,553	7.3	0.201	0.146	0.73
Illinois	669,891	488,132	15.4	0.310	0.226	0.73
Indiana	479,505	443,378	17.0	0.274	0.254	0.92
Iowa	177,874	129,612	8.5	0.263	0.191	0.73
Kansas	288,317	224,359	10.7	0.310	0.241	0.78
Kentucky	984,663	717,499	36.5	0.313	0.228	0.73
Louisiana	1,585,823	1,155,549	46.6	0.435	0.317	0.73
Maine	445,519	324,639	55.1	0.242	0.176	0.73
Maryland	857,152	624,585	39.8	0.353	0.257	0.73
Massachusetts	1,093,110	796,521	56.8	0.278	0.203	0.73
Michigan	1,410,284	1,027,638	34.4	0.241	0.175	0.73
Minnesota	325,047	236,853	13.0	0.251	0.183	0.73
Mississippi	1,630,583	1,188,165	56.9	0.377	0.275	0.73
Missouri	878,510	640,148	23.0	0.313	0.228	0.73
Montana	45,414	33,092	4.8	0.201	0.147	0.73
Nebraska	97,770	82,504	7.3	0.261	0.220	0.84
Nevada	35,783	26,074	4.8	0.226	0.165	0.73
New Hampshire	392,480	285,990	58.8	0.238	0.174	0.73
New Jersey	961,860	700,883	40.4	0.321	0.234	0.73
New Mexico	188,804	137,577	10.1	0.288	0.210	0.73
New York	1,606,981	1,170,966	39.6	0.263	0.192	0.73
North Carolina	3,457,794	2,519,606	53.7	0.341	0.249	0.73
North Dakota	18,730	8,900	1.7	0.244	0.116	0.48
Ohio	1,276,930	930,467	28.0	0.271	0.198	0.73
Oklahoma	718,922	523,860	21.9	0.364	0.265	0.73
Oregon	674,472	491,470	39.6	0.265	0.193	0.73
Pennsylvania	1,900,962	1,385,183	39.9	0.267	0.195	0.73
Rhode Island	127,720	93,066	49.6	0.283	0.206	0.73
South Carolina	2,052,656	1,495,718	53.3	0.370	0.269	0.73
South Dakota	29,351	25,453	2.8	0.258	0.224	0.87
Tennessee	1,678,890	1,501,125	40.8	0.332	0.297	0.89
Texas	4,416,309	3,218,052	28.2	0.403	0.294	0.73
Utah	119,794	87,291	11.6	0.235	0.172	0.73
Vermont	188,016	137,002	50.2	0.234	0.170	0.73
Virginia	2,111,293	1,538,445	52.5	0.321	0.234	0.73
Washington	1,139,218	830,119	37.3	0.282	0.206	0.73
West Virginia	774,594	564,427	63.6	0.264	0.192	0.73
Wisconsin	711,938	518,771	25.7	0.246	0.180	0.73
Wyoming	29,558	21,538	4.7	0.199	0.145	0.73
Total	**51,287,245**	**37,768,294**				

Uncertainty

Uncertainty associated with changes in carbon stocks in settlement trees includes the uncertainty associated with settlement area, percent tree cover in developed land and how well it represents percent tree cover in settlement areas, and estimates of gross and net carbon sequestration for each of the 50 states and the District of Columbia. A

ten percent uncertainty was associated with settlement area estimates based on expert judgment. Uncertainty associated with estimates of percent settlement tree coverage for each of the 50 states was based on standard error associated with the photo-interpretation of national tree cover in developed lands. Uncertainty associated with estimates of gross and net carbon sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates (Table 6-127). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass models, conversion factors, and decomposition assumptions used to calculate carbon sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil carbon stocks, and there is likely some overlap between the settlement tree carbon estimates and the forest tree carbon estimates (e.g., Nowak et al. 2013). Due to data limitations, settlement soil flux is not quantified as part of this analysis, while reconciliation of settlement tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate in 2022. The results of this quantitative uncertainty analysis are summarized in Table 6-127. The change in carbon stocks in settlement trees in 2022 was estimated to be between -208.5 and -66.6 MMT CO_2 Eq. at a 95 percent confidence level. This analysis indicates a range of 51 percent more sequestration to 52 percent less sequestration than the 2022 flux estimate of -138.5 MMT CO_2 Eq.

Table 6-127: Approach 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Changes in Carbon Stocks in Settlement Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Flux Estimate	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		(MMT CO_2 Eq.)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Settlement Trees	CO_2	(138.5)	(208.5)	(66.6)	-51%	+52%

[a] Range of C stock change estimates predicted by Monte Carlo stochastic simulation with a 95 percent confidence interval.

Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for settlement trees included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

The compilation methods remained the same in the latest *Inventory* relative to the previous *Inventory*. New data from the NRI and NLCD resulted in a small decrease in the settlement area for 2021, leading to no substantial change in the net carbon sequestration (Table 6-128).

Table 6-128: Recalculations of the Settlement Tree Categories

Category	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Settlement Area (km^2)	469,705	469,600	471,851
Settlement Tree Coverage (km^2)	151,694	151,664	152,442
Net C Flux (MMT C)	(37.6)	(37.6)	(37.8)

Net CO_2 Flux MMT CO_2 Eq.	(137.8)	(137.8)	(138.5)

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in Section 6.1, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between settlement trees and the forest land categories. Estimates for settlement trees are based on tree cover in settlement areas. Work is needed to clarify how much of this settlement area tree cover may also be accounted for in "forest" area assessments as some of these forests may be adjacent to settlement areas. For example, "forest" as defined by the USDA Forest Service Forest Inventory and Analysis (FIA) program fall within urban areas. Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the carbon reported in the forest source category might also be counted in the urban areas. The potential overlap with settlement areas is unknown at this time but research is underway to develop spatially explicit and spatially continuous land representation products which will eliminate the potential for double counting. Future research may also enable more complete coverage of changes in the carbon stock of trees for all settlements land.

N_2O Emissions from Settlement Soils (CRT Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 1 to 2 percent are currently applied to lawns, golf courses, and other landscaping within settlement areas, and contributes to soil N_2O emissions. The area of settlements is considerably smaller than other land uses that are managed with fertilizer, particularly cropland soils, and therefore, settlements account for a smaller proportion of total synthetic fertilizer application in the United States. In addition to synthetic N fertilizers, a portion of surface applied biosolids (i.e., treated sewage sludge) is used as an organic fertilizer in settlement areas, and drained organic soils (i.e., soils with high organic matter content, known as *histosols*) also contribute to emissions of soil N_2O.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions in the form of synthetic fertilizers and biosolids as well as enhanced mineralization of N in drained organic soils. Indirect emissions result from fertilizer and biosolids N that is transformed and transported to another location in a form other than N_2O (i.e., volatilization of ammonia [NH_3] and nitrogen oxide [NO_x], and leaching/runoff of nitrate [NO_3^-]), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from soils in settlements remaining settlements[100] are 2.5 MMT CO_2 Eq. (10 kt of N_2O) in 2022. There is an overall increase of 23 percent from 1990 to 2022 due to an expanding settlement area leading to more synthetic N fertilizer applications that peaked in the mid-2000s. Inter-annual variability in these emissions is directly attributable to variability in total synthetic fertilizer consumption, area of drained organic soils, and biosolids applications in the United States. Emissions from this source are summarized in Table 6-129.

Table 6-129: N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.							
Direct N_2O Emissions from Soils	**1.7**	**2.6**	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**
Synthetic Fertilizers	0.8	1.5	0.8	0.8	0.8	0.8	0.8

[100] Estimates of Soil N_2O for settlements remaining settlements include emissions from land converted to settlements because it was not possible to separate the activity data.

Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.8	1.0	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Emissions from Soils	**0.3**	**0.5**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**2.1**	**3.1**	**2.4**	**2.5**	**2.5**	**2.5**	**2.5**
kt N_2O							
Direct N_2O Emissions from Soils	**7**	**10**	**8**	**8**	**8**	**8**	**8**
Synthetic Fertilizers	3	5	3	3	3	3	3
Biosolids	1	1	1	1	1	1	1
Drained Organic Soils	3	4	4	4	4	4	4
Indirect N_2O Emissions from Soils	**1**	**2**	**1**	**1**	**1**	**1**	**1**
Total	**8**	**12**	**9**	**9**	**9**	**10**	**10**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

For settlement soils, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer, biosolids additions, and drained organic soils. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in biosolids applied to non-agricultural land and surface disposal (see Section 7.2 for a detailed discussion of the methodology for estimating biosolids available for non-agricultural land application), and the area of drained organic soils within settlements.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Brakebill and Gronberg 2017). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1987 through 2012 (Brakebill and Gronberg 2017). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2013 through 2017 are based on 2012 values adjusted for total annual total N fertilizer sales in the United States (AAPFCO 2016 through 2022) because there are no activity data on non-farm application after 2012. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. Since the total N fertilizer sales is only available through 2017 (AAPFCO 2022), the amount of synthetic fertilization from 2018 to 2022 is determined using a linear extrapolation method (see Box 6-4 in cropland remaining cropland). This method is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2017 fertilization data. To estimate direct N_2O for the time series, the total amount of fertilizer N applied to settlements is multiplied by the IPCC default emission factor (1 percent) (IPCC 2006) for 1990 to 2022.

Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2 for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (one percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2022.

The IPCC (2006) Tier 1 method is also used to estimate direct N_2O emissions due to drainage of organic soils in settlements at the national scale. Estimates of the total area of drained organic soils are obtained from the 2017 National Resources Inventory (NRI) (USDA-NRCS 2020) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The NRI time series has been extended through 2020 using the National Land Cover Dataset (Yang et al. 2018). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. To estimate annual emissions from 1990 to 2020, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). The annual emissions for 2021 to 2022 are estimated using a linear extrapolation method (see Box 6-4 in Cropland Remaining Cropland). This *Inventory* does not include soil N_2O emissions from drainage of organic soils in Alaska and federal lands, although this is a planned improvement for a future *Inventory*.

For indirect emissions, the total N applied from fertilizer and biosolids is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the

amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions from 1990 to 2022 for biosolids and synthetic fertilization.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2022 for biosolids. For synthetic fertilizer, a linear extrapolation method is used to approximate fertilizer application for the remainder of the 2018 to 2022 time series and then used to estimate emissions. For drainage of organic soils, the methods described above are applied for 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 time series (see Box 6-4 in cropland remaining cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The time series will be recalculated in a future *Inventory* with the methods described previously for drainage of organic soils.

Uncertainty

The amount of N_2O emitted from settlement soils depends not only on N inputs and area of drained organic soils, but also on a large number of variables that can influence rates of nitrification and denitrification, including organic C availability; rate, application method, and timing of N input; oxygen gas partial pressure; soil moisture content; pH; temperature; and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O emissions is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate these variables, except variation in the total amount of fertilizer N and biosolids application, which leads to uncertainty in the results.

Uncertainties exist in both the fertilizer N and biosolids application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[101] For emissions from drained organic soils, the total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was incorporated into the analysis for the latter part of the time series.

Uncertainty is propagated through the calculations of N_2O emissions from fertilizer N and drainage of organic soils based on a Monte Carlo analysis. The results are combined with the uncertainty in N_2O emissions from the biosolids application using simple error propagation methods (IPCC 2006). The results are summarized in Table 6-130. Direct N_2O emissions from soils in settlements remaining settlements in 2022 are estimated to be between 1.2 and 3.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 54 percent above the 2022 emission estimate of 2.2 MMT CO_2 Eq. Indirect N_2O emissions in 2022 are between 0.1 and 1.1 MMT CO_2 Eq., ranging from 76 percent below to 218 percent above the estimate of 0.3 MMT CO_2 Eq.

[101] No uncertainty is provided with the USGS fertilizer consumption data (Brakebill and Gronberg 2017) so a conservative ±50 percent is used in the analysis. Biosolids data are also assumed to have an uncertainty of ±50 percent.

Table 6-130: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements						
Direct N_2O Emissions from Soils	N_2O	2.2	1.2	3.4	-47%	+54%
Indirect N_2O Emissions from Soils	N_2O	0.3	0.1	1.1	-76%	+218%

[a] Range of emission estimates is a 95 percent confidence interval.

Note: These estimates include direct and indirect N_2O emissions from settlements remaining settlements and land converted to settlements because it was not possible to separate the activity data.

QA/QC and Verification

The spreadsheet containing fertilizer, drainage of organic soils, and biosolids applied to settlements and calculations for N_2O and uncertainty ranges have been checked consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). An error was found in the initial calculations for emissions from drained organic soils, which was corrected.

Recalculations Discussion

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. In addition, recalculations are associated with revised fertilizer application data from the AAPFCO report. As a result of these changes, CO_2-equivalent emissions changed annually with an average annual increase of 0.36 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in Alaska and federal lands in order to provide a complete inventory of emissions for this category. Data on fertilizer amounts from 2018 to 2022 will be updated after data are released for the latter part of the time series. These improvements will be incorporated into a future I*nventory*, pending prioritization of resources.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRT Category 4E1)

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. A portion of the carbon contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates within the *Inventory* are associated with particular land uses. For example, harvested wood products are reported under forest land remaining forest land because these wood products originated from the forest ecosystem. Similarly, carbon stock changes in yard trimmings and food scraps are reported under settlements remaining settlements because the bulk of the carbon, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this *Inventory*

they are reported with the yard trimmings in the settlements remaining settlements section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1), and reporting these carbon stock changes that occur entirely within landfills fits most appropriately within the settlements remaining settlements section. The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, see Section 7.1.

The estimated amount of yard trimmings collected annually has stagnated since 1990 and the fraction that is landfilled has been declining since 1990. From 1970 to 1990, yard trimmings collected for disposal increased by about 51 percent. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps are estimated to have been generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2020). Since then, programs banning or discouraging yard trimmings disposal in landfills have led to an increase in backyard composting and the use of mulching mowers, and consequently a slowing of year-over-year increases in the tonnage of yard trimmings generated. From 1990 to 2022, yard trimmings collected for disposal are estimated to have increased 1.1. percent. At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills per year—from 72 percent in 1990 to 30 percent in 2022. The net effect of the slight increase in generation and the increase in composting is a 58 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990. Composting trends and emissions estimations are presented in the Waste chapter, Section 7.3 composting.

Food scrap generation has grown by an estimated 165 percent since 1990. Though the proportion of total food scraps generated that are eventually discarded in landfills has decreased from an estimated 82 percent in 1990 to 55 percent in 2020, the tonnage disposed of in landfills has increased considerably (by an estimated 78 percent) due to the increase in food scrap generation. Although the total tonnage of food scraps disposed of in landfills has increased from 1990 to 2022, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual *net changes* in carbon stock from food scraps have generally decreased as well (as shown in Table 6-131 and Table 6-132). Landfilled food scraps decompose over time, producing CH_4 and CO_2. Decomposition happens at a higher rate initially, then decreases. As decomposition decreases, the carbon stock becomes more stable. Because the cumulative carbon stock left in the landfill from previous years is (1) not decomposing as much as the carbon introduced from food scraps in a single more recent year; and (2) is much larger than the carbon introduced from food scraps in a single more recent year, the total carbon stock in the landfill is primarily driven by the more stable "older" carbon stock, thus resulting in decreasing annual changes in later years.

Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in the annual net change in landfill carbon storage from 24.5 MMT CO_2 Eq. (6.7 MMT C) in 1990 to 11.8 MMT CO_2 Eq. (3.2 MMT C) in 2022 (Table 6-131 and Table 6-132), a decrease of 48 percent over the time series.

Table 6-131: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(20.1)**	**(7.5)**	**(8.3)**	**(8.2)**	**(8.2)**	**(8.2)**	**(8.1)**
Grass	(1.7)	(0.6)	(0.8)	(0.8)	(0.8)	(0.8)	(0.7)
Leaves	(8.7)	(3.4)	(3.8)	(3.8)	(3.8)	(3.8)	(3.7)
Branches	(9.8)	(3.4)	(3.7)	(3.7)	(3.7)	(3.7)	(3.6)
Food Scraps	**(4.4)**	**(3.9)**	**(5.2)**	**(4.8)**	**(4.5)**	**(4.3)**	**(3.7)**
Total Net Flux	**(24.5)**	**(11.4)**	**(13.4)**	**(13.1)**	**(12.8)**	**(12.5)**	**(11.8)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-132: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(5.5)**	**(2.0)**	**(2.3)**	**(2.2)**	**(2.2)**	**(2.2)**	**(2.2)**
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.4)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Branches	(2.7)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Food Scraps	**(1.2)**	**(1.1)**	**(1.4)**	**(1.3)**	**(1.2)**	**(1.2)**	**(1.0)**
Total Net Flux	**(6.7)**	**(3.1)**	**(3.7)**	**(3.6)**	**(3.5)**	**(3.4)**	**(3.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the carbon that remains is effectively removed from the carbon cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of carbon in landfills can increase, with the net effect being removal of carbon from the atmosphere. Estimates of the net carbon flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled carbon stocks between inventory years and uses a country-specific methodology based on the methodology for estimating the amount of harvested wood products stored in solid waste disposal systems that is provided in the Land Use, Land-Use Change, and Forestry sector in IPCC (2003) and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Carbon stock estimates were calculated by determining the mass of landfilled carbon resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled carbon from previous years; and subtracting the mass of carbon that was landfilled in previous years and has since decomposed and been emitted as CO_2 and CH_4.

To determine the total landfilled carbon stocks for a given year, the following data and factors were assembled:

(1) The composition of the yard trimmings (i.e., the proportion of grass, leaves and branches);

(2) The mass of yard trimmings and food scraps discarded in landfills;

(3) The carbon storage factor of the landfilled yard trimmings and food scraps; and

(4) The rate of decomposition of the degradable carbon.

The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted carbon storage factor (i.e., based on differences in moisture content and carbon content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2010, 2015, 2017 and 2018. To provide data for some of the missing years, detailed backup data were obtained from the 2012, 2013, and 2014, 2015, and 2017 versions of the *Advancing Sustainable Materials Management: Facts and Figures* reports (EPA 2019), as well as historical data tables that EPA developed for 1960 through 2012 (EPA 2016). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Since the *Advancing Sustainable Materials Management: Facts and Figures* reports for 2019 through 2022 were unavailable, landfilled material generation, recovery, and disposal data for 2019 through 2022 were proxied equal to 2018 values.

The amount of carbon disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying

by the initial (i.e., pre-decomposition) carbon content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial carbon contents and the carbon storage factors were determined by Barlaz (1998, 2005, 2008).

The amount of carbon remaining in the landfill for each subsequent year was tracked based on a simple model of carbon fate based on a laboratory experiment simulating decomposition of landfilled biogenic materials by methanogenic microbes (Barlaz 1998, 2005, 2008). Carbon remaining in landfilled materials is expressed as a proportion of initial carbon content, shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-133.

The modeling approach applied to simulate U.S. landfill carbon flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of carbon stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2.[102] The degradable portion of the carbon is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-133.

The first-order decay rates, *k*, for each waste component are derived from De la Cruz and Barlaz (2010):

- De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is calculated so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed municipal solid waste (MSW) for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, De la Cruz and Barlaz used 1990 waste composition for the United States from EPA's *Characterization of Municipal Solid Waste in the United States: 1990 Update* (EPA 1991) to calculate *f*. De la Cruz and Barlaz multiplied this correction factor by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.
- De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, k=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, k=0.12).

Similar to the methodology in the Landfills section of the *Inventory* (Section 7.1), which estimates CH_4 emissions, the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 $year^{-1}$, respectively. De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 $year^{-1}$), but not for the other two overall MSW decay rates.

To maintain consistency between landfill-related methodologies across the *Inventory*, EPA developed correction factors (*f*) for decay rates of 0.038 and 0.057 $year^{-1}$ through linear interpolation. A weighted national average component-specific decay rate is calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The percent of census population is calculated for each of the three categories of annual precipitation (noted in the previous paragraph); the population data are used as a surrogate for the number of landfills in each annual precipitation category. Precipitation range percentages weighted by population are updated over time as new Census data are available, to remain consistent with percentages used in the Waste chapter, Section 7.1 landfills. The component-specific decay rates are shown in Table 6-133.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including

[102] The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, Section 7.1—Landfills.

dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

For each of the four materials (grass, leaves, branches, food scraps), the stock of carbon in landfills for any given year is calculated according to Equation 6-2:

Equation 6-2: Total Carbon Stock for Yard Trimmings and Food Scraps in Landfills

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \left\{[CS_i \times ICC_i] + \left[\left(1 - (CS_i \times ICC_i)\right) \times e^{-k(t-n)}\right]\right\}$$

where,

t	=	Year for which carbon stocks are being estimated (year),
i	=	Waste type for which carbon stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$	=	Stock of carbon in landfills in year *t*, for waste *i* (metric tons),
$W_{i,n}$	=	Mass of waste *i* disposed of in landfills in year *n* (metric tons, wet weight),
n	=	Year in which the waste was disposed of (year, where 1960 < *n* < *t*),
MC_i	=	Moisture content of waste *i* (percent of water),
CS_i	=	Proportion of initial carbon that is stored for waste *i* (percent),
ICC_i	=	Initial carbon content of waste *i* (percent),
e	=	Natural logarithm, and
k	=	First-order decay rate for waste *i*, (year^{-1}).

For a given year *t*, the total stock of carbon in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of carbon in landfills (F_t) for year *t* is calculated in as the change in carbon stock compared to the preceding year according to Equation 6-3:

Equation 6-3: Carbon Stock Annual Flux for Yard Trimmings and Food Scraps in Landfills

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 6-2, the carbon placed in a landfill in year *n* is tracked for each year *t* through the end of the inventory period. For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of carbon in landfills. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (507,000 metric tons) decomposes, leaving a total of 628,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2022, the total food scraps carbon originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable carbon had decomposed). By summing the carbon remaining from 1960 with the carbon remaining from food scraps disposed of in subsequent years (1961 through 2021), the total landfill carbon from food scraps in 2022 was 53.0 million metric tons. This value is then added to the carbon stock from grass, leaves, and branches to calculate the total landfill carbon stock in 2022, yielding a value of 292.6 million metric tons (as shown in Table 6-134). In the same way total net flux is calculated for forest carbon and harvested wood products, the total net flux of landfill carbon for yard trimmings and food scraps for a given year (Table 6-132) is the difference in the landfill carbon stock for the following year and the stock in the current year. For example, the net change in 2022 shown in Table 6-132 (3.2 MMT C with rounding) is equal to the stock in 2023 (295.9 MMT C) minus the stock in 2022 (292.6 MMT C). The carbon stocks calculated through this procedure are shown in Table 6-134.

To develop the 2023 carbon stock estimate, estimates of yard trimming and food scrap carbon stocks were forecasted for 2023, based on data from 1990 through 2022. These forecasted values were used to calculate net changes in carbon stocks for 2022. Excel's FORECAST.ETS function was used to predict a 2023 value using historical data via an algorithm called "Exponential Triple Smoothing." This method determined the overall trend and provided appropriate carbon stock estimates for 2023.

Table 6-133: Moisture Contents, Carbon Storage Factors (Proportions of Initial Carbon Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate ($year^{-1}$)	0.313	0.179	0.015	0.151

Note: The decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category.

Table 6-134: Carbon Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022	2023
Yard Trimmings	**156.0**	**203.1**	**231.6**	**233.9**	**236.1**	**238.4**	**240.6**	**242.8**
Branches	14.6	18.1	20.7	20.9	21.1	21.3	21.6	21.8
Leaves	66.7	87.4	100.4	101.5	102.5	103.6	104.6	105.6
Grass	74.7	97.7	110.5	111.5	112.5	113.5	114.5	115.4
Food Scraps	**17.9**	**33.2**	**46.9**	**48.3**	**49.6**	**50.9**	**52.0**	**53.0**
Total Carbon Stocks	**173.9**	**236.3**	**278.5**	**282.2**	**285.7**	**289.2**	**292.6**	**295.9**

[a] 2023 C stock estimate was forecasted using 1990 to 2022 data.

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. When available, the same data source was used across the entire time series for the analysis. When data were unavailable, missing values were estimated using linear interpolation or forecasting, as noted above.

Uncertainty

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of carbon), initial carbon content, moisture content, decay rate, and proportion of carbon stored. The carbon storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate for 2022. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-135. Total yard trimmings and food scraps CO_2 flux in 2022 was estimated to be between -17.3 and -4.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 58 percent above the 2022 flux estimate of -11.8 MMT CO_2 Eq.

Table 6-135: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2021 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(11.8)	(17.3)	(4.9)	-47%	+58%

[a] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Parentheses indicate negative values or net carbon sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan. Source-specific quality control measures for landfilled yard trimmings and food scraps included checking that input data were properly transposed within the spreadsheet, checking calculations were correct, and confirming that all activity data and calculations documentation was complete and updated to ensure data were properly handled through the inventory process.

Order of magnitude checks and checks of time-series consistency were performed to ensure data were updated correctly and any changes in emissions estimates were reasonable and reflected changes in activity data. An annual change trend analysis was also conducted to ensure the validity of the emissions estimates. Errors that were found during this process were corrected as necessary.

To ensure consistency across the LULUCF and Waste sectors, and the accuracy of emissions, EPA plans to perform a comparison of the activity data used and carbon inputs between the landfilled yard trimmings and food scraps, and the Waste chapter, Section 7.1—Landfills categories.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource constraints:

- MSW data more recent than 2018 have not been released through the *Advancing Sustainable Materials Management* reports. EPA will monitor the release schedule for these data and evaluate data for integration into the *Inventory* when released. Six new food waste management pathways were introduced in the 2018 *Advancing Sustainable Materials Management* report. Time series data for all of these pathways are not provided prior to 2018 but EPA plans to investigate potential data sources and/or methods to address time-series consistency and apply these data to the time series.
- EPA has been made aware of inconsistencies in landfilled food scraps data reported to the EPA Greenhouse Gas Reporting Program (GHGRP) and will evaluate changes to how landfilled and energy recovery values for yard trimmings and food scraps are calculated.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement these improvements until data are available or identified:

- EPA also plans to continue to investigate updates to the decay rate estimates for food scraps, leaves, grass, and branches, as well as evaluate using decay rates that vary over time based on Census population

and climate data changes over time. Currently the inventory calculations use 2010 U.S. Census data, but 2020 U.S. Census data may be available.

- Other improvements include investigation into yard waste composition to determine if changes need to be made based on changes in residential practices. A review of available literature will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills. In addition, agronomists may be consulted for determining the mass of grass per acre on residential lawns to provide an estimate of total grass generation for comparison with *Inventory* estimates.
- EPA will continue to evaluate data from recent peer-reviewed literature that may modify the default carbon storage factors, initial carbon contents, and decay rates for yard trimmings and food scraps in landfills – particularly updates to population precipitation ranges used to calculate k values. Based upon this evaluation, changes may be made to the default values.
- Finally, EPA plans to review available data to ensure all types of landfilled yard trimmings and food scraps are being included in the *Inventory* estimates, such as debris from road construction and commercial food waste not included in other *Inventory* estimates.

6.11 Land Converted to Settlements (CRT Category 4E2)

Land converted to settlements includes all settlements in an inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[103] For example, cropland, grassland or forest land converted to settlements during the past 20 years would be reported in this category. Converted lands are retained in this category for 20 years as recommended by IPCC (2006).

Land use change can lead to large losses of carbon to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining globally (Tubiello et al. 2015). IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic carbon stocks due to land-use change. All soil organic carbon stock changes are estimated and reported for land converted to settlements, but there is limited reporting of other pools in this *Inventory.* Loss of aboveground and belowground biomass, dead wood and litter carbon are reported for forest land converted to settlements and woodlands associated with grasslands converted to settlements, but not for other land-use conversions to settlements.

There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for land converted to settlements. Specifically, this *Inventory* includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils in settlements on federal lands are also not included in this *Inventory.* These differences lead to discrepancies between the managed area in land converted to settlements and the settlement area included in the inventory analysis (Table 6-129). There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future *Inventory* (see Planned Improvements section).

[103] NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of land converted to settlements in the early part of the time series to the extent that some areas are converted to settlements from 1971 to 1978.

Forest land converted to settlements is the largest source of emissions from 1990 to 2022, accounting for approximately 76 percent of the average total loss of carbon among all of the land-use conversions in Land Converted to Settlements. Total losses of aboveground and belowground biomass, dead wood and litter carbon losses in 2022 for all conversions are 35.6, 6.2, 6.7, and 9.2 MMT CO_2 Eq., respectively (9.7, 1.7, 1.8, and 2.5 MMT C). Mineral and organic soils also lost 9.2 and 1.3 MMT CO_2 Eq. in 2022 (2.5 and 0.3 MMT C). The total net flux is 68.2 MMT CO_2 Eq. in 2022 (18.6 MMT C), which is a 19 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990 (Table 6-136 and Table 6-137). The main driver of net emissions for this source category is the conversion of forest land to settlements, with large losses of biomass, deadwood and litter carbon.

Table 6-136: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**2.6**	**8.2**	**3.9**	**3.5**	**3.1**	**2.9**	**2.9**
Mineral Soils	2.1	6.9	3.4	2.9	2.6	2.5	2.5
Organic Soils	0.5	1.2	0.6	0.5	0.4	0.4	0.4
Forest Land Converted to Settlements	**49.3**	**53.9**	**58.4**	**58.6**	**58.6**	**58.6**	**58.6**
Aboveground Live Biomass	30.0	32.4	35.0	35.2	35.2	35.2	35.2
Belowground Live Biomass	5.2	5.6	6.1	6.1	6.1	6.1	6.1
Dead Wood	5.5	6.0	6.5	6.6	6.6	6.6	6.6
Litter	7.6	8.2	9.0	9.0	9.0	9.0	9.0
Mineral Soils	1.0	1.5	1.5	1.5	1.5	1.5	1.5
Organic Soils	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Grassland Converted to Settlements	**5.6**	**15.8**	**9.8**	**8.8**	**7.9**	**7.4**	**7.5**
Aboveground Live Biomass	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Belowground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Litter	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mineral Soils	4.3	13.7	8.2	7.3	6.5	6.0	6.0
Organic Soils	0.5	1.3	0.7	0.6	0.5	0.5	0.6
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(1.1)**	**(1.0)**	**(0.8)**	**(0.8)**	**(0.8)**
Mineral Soils	(0.4)	(1.5)	(1.1)	(1.0)	(0.9)	(0.8)	(0.8)
Organic Soils	+	0.1	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.6**	**0.3**	**0.3**	**0.1**	+	**0.1**
Mineral Soils	+	0.1	+	+	+	+	+
Organic Soils	+	0.6	0.3	0.3	+	+	+
Total Aboveground Biomass Flux	**30.4**	**32.8**	**35.5**	**35.6**	**35.6**	**35.6**	**35.6**
Total Belowground Biomass Flux	**5.2**	**5.7**	**6.1**	**6.2**	**6.2**	**6.2**	**6.2**
Total Dead Wood Flux	**5.6**	**6.1**	**6.7**	**6.7**	**6.7**	**6.7**	**6.7**
Total Litter Flux	**7.7**	**8.4**	**9.2**	**9.2**	**9.2**	**9.2**	**9.2**
Total Mineral Soil Flux	**7.0**	**20.7**	**12.0**	**10.8**	**9.8**	**9.2**	**9.2**
Total Organic Soil Flux	**1.2**	**3.4**	**1.8**	**1.6**	**1.3**	**1.2**	**1.3**
Total Net Flux	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-137: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**0.7**	**2.2**	**1.1**	**1.0**	**0.8**	**0.8**	**0.8**
Mineral Soils	0.6	1.9	0.9	0.8	0.7	0.7	0.7
Organic Soils	0.1	0.3	0.2	0.1	0.1	0.1	0.1

Forest Land Converted to Settlements	**13.5**	**14.7**	**15.9**	**16.0**	**16.0**	**16.0**	**16.0**
Aboveground Live Biomass	8.2	8.8	9.6	9.6	9.6	9.6	9.6
Belowground Live Biomass	1.4	1.5	1.7	1.7	1.7	1.7	1.7
Dead Wood	1.5	1.6	1.8	1.8	1.8	1.8	1.8
Litter	2.1	2.2	2.5	2.5	2.5	2.5	2.5
Mineral Soils	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Converted to Settlements	**1.5**	**4.3**	**2.7**	**2.4**	**2.2**	**2.0**	**2.0**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	0.1	0.1	0.1	0.1	0.1
Mineral Soils	1.2	3.7	2.2	2.0	1.8	1.6	1.6
Organic Soils	0.1	0.3	0.2	0.2	0.1	0.1	0.2
Other Lands Converted to Settlements	**(0.1)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.2)**
Mineral Soils	(0.1)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.2**	**0.1**	**0.1**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.2	0.1	0.1	+	+	+
Total Aboveground Biomass Flux	**8.3**	**8.9**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**
Total Belowground Biomass Flux	**1.4**	**1.5**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Total Dead Wood Flux	**1.5**	**1.7**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
Total Litter Flux	**2.1**	**2.3**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total Mineral Soil Flux	**1.9**	**5.6**	**3.3**	**2.9**	**2.7**	**2.5**	**2.5**
Total Organic Soil Flux	**0.3**	**0.9**	**0.5**	**0.4**	**0.4**	**0.3**	**0.3**
Total Net Flux	**15.6**	**21.0**	**19.5**	**19.1**	**18.8**	**18.6**	**18.6**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate carbon stock changes for land converted to settlements, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with conversion to settlements from forest lands and woodlands designated in the grassland, as well as (2) the impact from all land-use conversions to settlements on soil organic carbon stocks in mineral and organic soils.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter carbon stock changes for forest land converted to settlements. Estimates are calculated in the same way as those in the forest land remaining forest land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2023) however there is no country-specific data for settlements so the biomass, litter, and dead wood carbon stocks were assumed to be zero. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this *Inventory*, it was assumed that 10 percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

This *Inventory* also includes estimates of change in dead organic matter for standing dead, deadwood and litter. If FIA plots include data on standing dead trees, standing dead tree carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011 and Westfall et al. 2023) with additional modifications for woodland species to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood carbon density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood carbon estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. See Annex 3.13 for more information about reference carbon density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to settlements according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021; Johnson and Mueller 2010) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015)). For federal lands, the land use history is derived from land cover changes in the NLCD. The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 for more information). Land use and some management information were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data have been incorporated from the NRI into the inventory analysis through 2017 (USDA-NRCS 2020).

NRI survey locations are classified as land converted to settlements in a given year between 1990 and 2020 if the land use is settlements but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of land converted to settlements in the early part of the time series to the extent that some areas are converted to settlement between 1971 and 1978.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate carbon stock changes for mineral soils on land converted to settlements from 1990 to 2020. Data on climate, soil types, land use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference carbon stocks are estimated using the National Soil Survey Characterization Database (USDA-NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (USDA-NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provide a more robust sample for estimating the reference condition. Country-specific carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon storage (Ogle et al. 2003; Ogle et al. 2006). However, there are insufficient data to estimate a set of land use, management, and input factors for settlements. Moreover, the 2017 NRI survey data (USDA-NRCS 2020) do not provide the information needed to assign different land use subcategories to settlements, such as

turf grass and impervious surfaces, which is needed to apply the Tier 1 factors from the IPCC guidelines (2006). Therefore, the United States has adopted a land use factor of 0.7 to represent a net loss of soil organic carbon with conversion to settlements under the assumption that there are additional soil organic carbon losses with land clearing, excavation and other activities associated with development. More specific factor values can be derived in future Inventories as data become available. See Annex 3.12 for additional discussion of the Tier 2 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in Cropland Remaining Cropland. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to settlements are estimated using the Tier 2 method provided in IPCC (2006). The Tier 2 method assumes that organic soils are losing carbon at a rate similar to croplands, and therefore uses the country-specific values for cropland (Ogle et al. 2003). To estimate CO_2 emissions from 1990 to 2020, the area of organic soils in land converted to settlements is multiplied by the Tier 2 emission factor, which is 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 time series (see Box 6-4 of the Methodology section in Cropland Remaining Cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). Estimates will be recalculated in future *Inventories* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analysis for carbon losses with forest land converted to settlements is conducted in the same way as the uncertainty assessment for forest ecosystem carbon flux in the forest land remaining forest land category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Sources of uncertainty for mineral soil organic carbon stock changes and annual carbon emission estimates from drained organic soils include emission factors and variance associated with the NRI sample. The total uncertainty was quantified with two variance components (Ogle et al. 2010) that are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For the first variance component, a Monte Carlo analysis was used to propagate uncertainties in the Tier 2 methods for the land use area and the country-specific factors or mineral and organic soils. The second variance component is associated with scaling of the data from the NRI survey to the entire area of land converted to settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992).

Uncertainty estimates are presented in Table 6-138 for each sub-source (i.e., biomass carbon, dead wood, litter, soil organic carbon in mineral soils and organic soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates are combined from the forest land converted to settlements and other land use conversions to settlements using the simple error propagation methods provided by the IPCC (2006). There are

also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil organic carbon stock changes from 2021 to 2022. The combined uncertainty for total carbon stock changes in land converted to settlements ranges from 36 percent below to 36 percent above the 2022 stock change estimate of 68.2 MMT CO_2 Eq.

Table 6-138: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Settlements (MMT CO_2 Eq. and Percent)

Source	2022 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Settlements	**2.9**	**1.3**	**4.5**	**-56%**	**56%**
Mineral Soil C Stocks	2.5	0.9	4.1	-64%	63%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-146%	146%
Organic Soil C Stocks	0.4	0.1	0.7	-80%	80%
Forest Land Converted to Settlements	**58.6**	**35.3**	**81.9**	**-40%**	**40%**
Aboveground Biomass C Stocks	35.2	13.3	57.1	-62%	62%
Belowground Biomass C Stocks	6.1	2.3	9.9	-62%	62%
Dead Wood	6.6	2.5	10.6	-62%	62%
Litter	9.0	3.4	14.7	-62%	62%
Mineral Soil C Stocks	1.5	1.2	1.7	-19%	19%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.3	0.1	0.4	-70%	70%
Grassland Converted to Settlements	**7.4**	**5.4**	**9.5**	**-27%**	**27%**
Aboveground Biomass C Stocks	0.5	0.2	0.8	-62%	60%
Belowground Biomass C Stocks	0.1	0.0	0.1	-45%	66%
Dead Wood	0.2	0.1	0.3	-51%	70%
Litter	0.2	0.1	0.3	-61%	57%
Mineral Soil C Stocks	6.0	4.1	7.9	-32%	32%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-194%	194%
Organic Soil C Stocks	0.5	(0.0)	1.1	-108%	108%
Other Lands Converted to Settlements	**-0.8**	**(1.1)**	**(0.4)**	**-44%**	**44%**
Mineral Soil C Stocks	-0.8	(1.1)	(0.5)	-38%	38%
Federal Mineral Soil C Stocks	0.0	(0.2)	0.1	-738%	738%
Organic Soil C Stocks	0.0	(0.1)	0.1	-511%	511%
Wetlands Converted to Settlements	**0.1**	**(0.3)**	**0.3**	**-557%**	**533%**
Mineral Soil C Stocks	0.0	0.0	0.1	-69%	69%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.0	(0.3)	0.3	-1,269%	1,214%
Total: Land Converted to Settlements	**68.2**	**43.5**	**92.9**	**-36%**	**36%**
Aboveground Biomass C Stocks	**35.6**	**13.3**	**57.1**	**-62%**	**62%**
Belowground Biomass C Stocks	**6.2**	**2.3**	**9.9**	**-62%**	**62%**
Dead Wood	**6.7**	**2.5**	**10.6**	**-62%**	**62%**
Litter	**9.2**	**3.4**	**14.7**	**-62%**	**62%**
Mineral Soil C Stocks	**9.2**	**6.6**	**11.7**	**-28%**	**28%**
Organic Soil C Stocks	**1.2**	**(6.6)**	**9.1**	**-625%**	**625%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this *Inventory*.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks in forest land converted to settlements and woodland conversion associated with grassland converted to settlements. Additional recalculations are associated with incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. As a result, land converted to settlements has an estimated smaller carbon loss of 7.7 MMT CO_2 Eq. on average over the time series. This represents a 19 percent decrease in carbon stock changes for land converted to settlements compared to the previous *Inventory.*

Planned Improvements

A key improvement is to develop an inventory of mineral soil organic carbon stock changes in Alaska and losses of carbon from drained organic soils in federal lands. These improvements will resolve most of the differences between the managed land base for land converted to settlements and amount of area currently included in the *Inventory* for land converted to settlements (see Table 6-139).

There are plans to improve classification of trees in settlements and to include transfer of biomass from forest land to those areas in this category. There are also plans to extend the inventory to included carbon losses associated with drained organic soils in settlements occurring on federal lands.

These improvements will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-139: Area of Managed Land in Land Converted to Settlements that is not included in the current *Inventory* (Thousand Hectares)

	Area (Thousand Hectares)		
Year	LCS Managed Land Area (Section 6.1)	LCS Area Included in *Inventory*	LCS Area Not Included in *Inventory*
1990	2,865	2,865	1
1991	3,213	3,213	1
1992	3,573	3,573	1
1993	4,138	4,138	1
1994	4,703	4,702	1
1995	5,262	5,261	1
1996	5,833	5,832	1
1997	6,409	6,408	1
1998	6,929	6,928	1
1999	7,446	7,446	1
2000	7,952	7,952	1
2001	8,362	8,361	1
2002	8,696	8,695	1
2003	8,705	8,704	1
2004	8,710	8,708	2
2005	8,727	8,724	2

2006	8,691	8,688	3
2007	8,672	8,668	3
2008	8,501	8,497	4
2009	8,309	8,305	5
2010	8,130	8,124	5
2011	7,930	7,925	6
2012	7,717	7,711	6
2013	7,325	7,318	6
2014	6,942	6,935	7
2015	6,530	6,523	7
2016	6,112	6,105	7
2017	5,715	5,708	7
2018	5,201	5,194	7
2019	4,696	4,689	7
2020	4,175	4,168	7
2021	3,771	*	*
2022	3,437	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

6.12 Other Land Remaining Other Land (CRT Category 4F1)

Land use is constantly occurring, and areas under a number of differing land-use types remain in their respective land-use type each year, just as other land can remain as other land. While the magnitude of other land remaining other land is known (see Table 6-4), research is ongoing to track carbon pools in this land use. Until such time that reliable and comprehensive estimates of carbon for other land remaining other land can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on other land remaining other land at this time.

6.13 Land Converted to Other Land (CRT Category 4F2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to other land each year, just as other land is converted to other uses. While the magnitude of these area changes is known (see Table 6-4), research is ongoing to track carbon across other land remaining other land and land converted to other land. Until such time that reliable and comprehensive estimates of carbon across these land-use and land-use change categories can be produced, it is not possible to separate CO_2, CH_4 or N_2O fluxes on land converted to other land from fluxes on other land remaining other land at this time.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1 and Figure 7-2). Landfills were the third largest source of anthropogenic methane (CH_4) in the United States in 2022, accounting for approximately 17.1 percent of total U.S. CH_4 emissions. Additionally, wastewater treatment and discharge, composting of organic waste, and anaerobic digestion at biogas facilities accounted for approximately 3.0 percent, 0.4 percent, and less than 0.1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions resulting from the discharge of wastewater treatment effluents into aquatic environments were estimated, along with the wastewater treatment process itself and composting. Together, these waste activities account for 6.1 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste sector is presented in Table 7-1 and Table 7-2. Overall, in 2022, waste activities generated emissions of 166.9 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions.

Emissions from landfills contributed 71.8 percent of Waste sector emissions in 2022 (see Figure 7-1) and are primarily composed of CH_4 emissions from municipal solid waste landfills. Landfill emissions decreased by 2.3 MMT CO_2 Eq. (1.9 percent) since 2021. Emissions from wastewater treatment were the second largest source of waste-related emissions in 2022, accounting for 25.6 percent of sector emissions. The remaining two sources of emissions, composting and anaerobic digestion at biogas facilities, account for 2.6 percent and less than 0.1 percent of Waste sector emissions in 2022, respectively.

Figure 7-1: 2022 Waste Sector Greenhouse Gas Sources

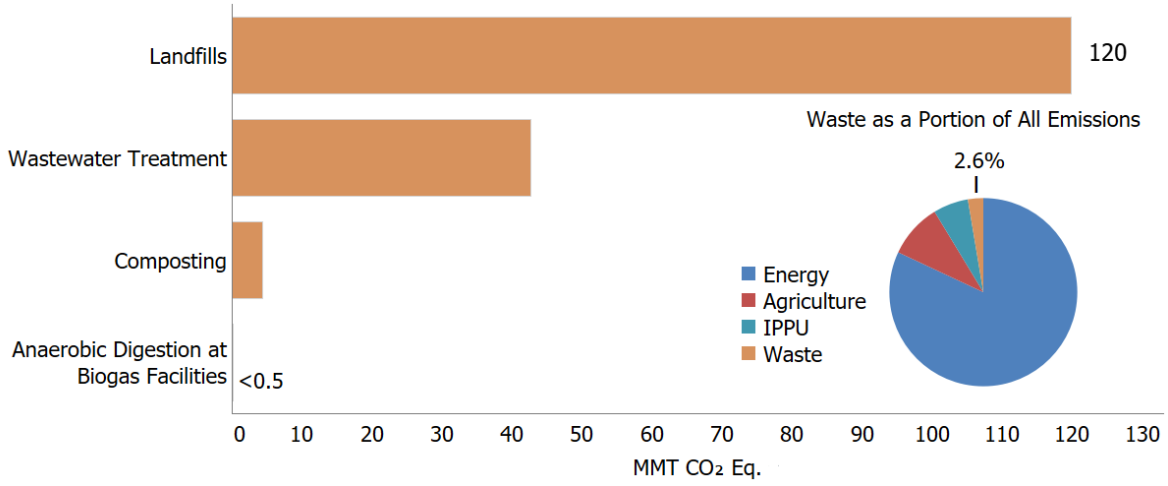


Figure 7-2: Trends in Waste Sector Greenhouse Gas Sources

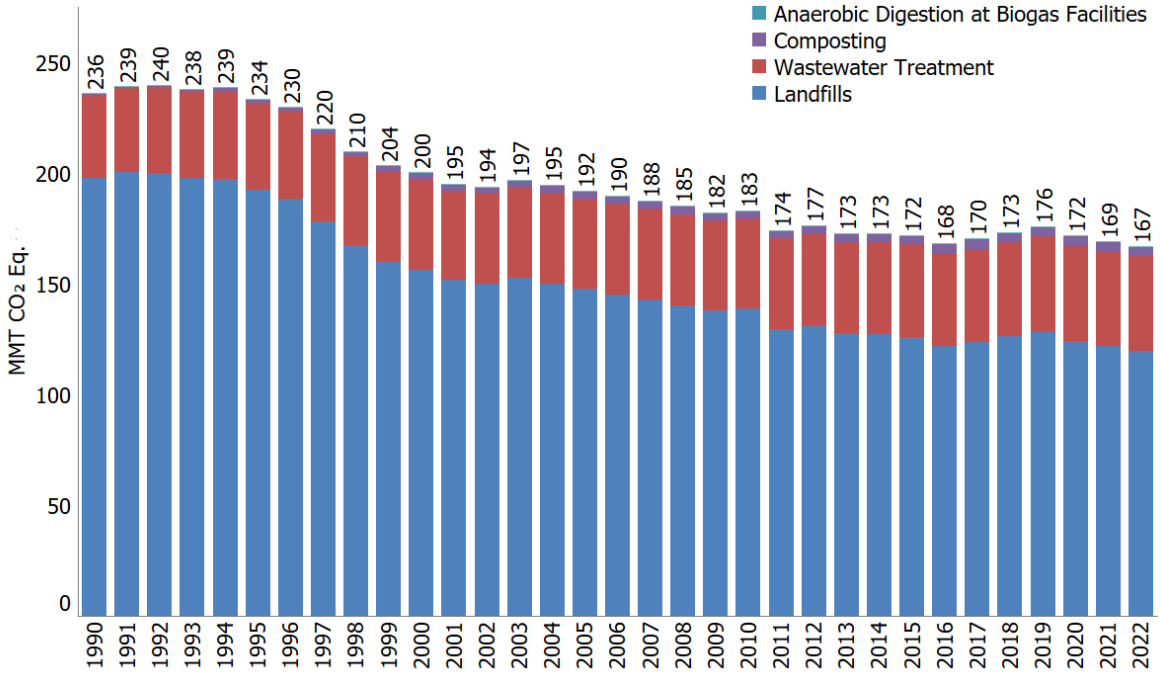


Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CH_4	**220.9**	**172.4**	**150.2**	**152.4**	**147.6**	**145.3**	**143.2**
Landfills	197.8	147.7	126.3	128.7	124.1	122.0	119.8
Wastewater Treatment	22.7	22.7	21.4	21.1	21.0	20.7	20.8
Composting	0.4	2.1	2.5	2.5	2.6	2.6	2.6
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+
N_2O	**15.1**	**19.5**	**23.0**	**23.4**	**24.1**	**23.9**	**23.7**
Wastewater Treatment	14.8	18.1	21.2	21.6	22.3	22.1	21.9
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Total	**235.9**	**192.0**	**173.2**	**175.8**	**171.7**	**169.2**	**166.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CH_4	**7,889**	**6,159**	**5,365**	**5,441**	**5,271**	**5,189**	**5,113**
Landfills	7,063	5,275	4,512	4,595	4,431	4,359	4,277
Wastewater Treatment	811	809	763	755	748	738	743
Composting	15	75	90	91	92	92	92
Anaerobic Digestion at Biogas Facilities	+	+	+	1	+	+	+
N_2O	**57**	**74**	**87**	**88**	**91**	**90**	**89**
Wastewater Treatment	56	68	80	81	84	83	83
Composting	1	6	7	7	7	7	7

+ Does not exceed 0.5 kt.

Note: Totals by gas may not sum due to independent rounding.

Carbon dioxide (CO_2), CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2022 resulted in 12.7 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.5. Greenhouse Gas Precursor Emissions from the Waste sector are presented in Section 7.6.

Each year, some emission and sink estimates in the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory*'s time series (i.e., 1990 to 2021) to ensure that the trend is accurate. For the current *Inventory*, minor improvements were implemented beyond routine activity data updates, including changes to MSW and industrial waste landfill activity data, updates to production activity affecting wastewater influent, and methodological changes for CH_4 emissions from anaerobic digesters processing food waste. In total, the methodological and historic data improvements made to the Waste sector in this *Inventory* resulted in an average decrease in greenhouse gas emissions across the time series by 0.06 MMT CO_2 Eq. (0.03 percent). For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Due to lack of data availability, EPA is not able to estimate emissions associated with sludge generated from the treatment of industrial wastewater. Emissions reported in the Waste chapter for landfills, wastewater treatment, and anaerobic digestion at biogas facilities include those from all 50 states, including Hawaii and Alaska, the District of Columbia, and U.S. Territories. Emissions from landfills include modern, managed sites in most U.S. Territories except for outlying Pacific Islands. Emissions from domestic wastewater treatment include most U.S. Territories except for outlying Pacific Islands. Those emissions are likely insignificant as those outlying Pacific Islands (e.g., Baker Island) have no permanent population. No industrial wastewater treatment emissions are estimated for U.S. Territories, due to lack of data availability. However, industrial wastewater treatment emissions are not expected for outlying Pacific Islands and assumed to be small for other U.S. Territories. Emissions for composting include Puerto Rico and all states except Alaska. Some composting operations in Alaska are known, but these consist of aerated composting facilities. Composting emissions are not included from the remaining U.S. Territories, and these are assumed to be small. Similarly, EPA is not aware of any anaerobic digestion at biogas facilities in U.S. Territories but will review this on an ongoing basis to include these emissions if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this *Inventory*.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to Greenhouse Gas Reporting Data

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines)* and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and sinks provided in the Waste chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from waste management and treatment activities.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. See Annex 9 "Use of EPA Greenhouse Gas Reporting Program in Inventory" for more information.

Waste Data from EPA's Greenhouse Gas Reporting Program

EPA uses annual GHGRP facility-level data in the Landfills category to compile the national estimate of emissions from Municipal Solid Waste (MSW) landfills (see Section 7.1 of this chapter for more information). EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2022 of the *Inventory*. MSW landfills subject to the GHGRP began collecting data in 2010. These data are also used to recalculate emissions from MSW landfills for the years 2005 to 2009 to ensure time-series consistency.

7.1 Landfills (CRT Source Category 5A1)

In In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-2. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current *Inventory* year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations [CFR] in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These CH_4 producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Box 7-2: Description of a Modern, Managed Landfill in the United States

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. A modern, managed landfill is EPA's interpretation of the IPCC's terminology of a managed solid waste disposal site. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream.

Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the NSPS 40 CFR Part 60 Subparts WWW and XXX.[1] Additionally, state and tribal requirements may exist.

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. Net carbon dioxide flux from carbon stock changes of materials of biogenic origin in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this *Inventory*). Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas–that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is

[1] For more information regarding federal MSW landfill regulations, see http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm.

disposed of in a landfill and will continue for 10 to 50 or more years as the degradable waste decomposes over time.

In 2022, landfill CH_4 emissions were approximately 119.8 MMT CO_2 Eq. (4,277 kt), representing the third largest source of CH_4 emissions in the United States, behind enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 84 percent of total landfill emissions (100.9 MMT CO_2 Eq.), while industrial waste landfills accounted for the remainder (18.9 MMT CO_2 Eq.). Nationally, there are significantly less industrial waste landfills compared to MSW landfills, which contributes to the lower national estimate of CH_4 emissions for industrial waste landfills. Additionally, the average organic content of waste streams disposed in industrial waste landfills is lower than MSW landfills. Estimates of operational MSW landfills in the United States have ranged from 1,700 to 2,000 facilities (EPA 2023a; EPA 2023b; EPA 2020c; Waste Business Journal [WBJ] 2016; WBJ 2010). The Environment Research & Education Foundation (EREF) conducted a nationwide analysis of MSW management and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, (EPA 2023b; WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to as few as 1,540 in 2013, the average landfill size has increased (EPA 2023a; EREF 2016; BioCycle 2010). Larger landfills may have deeper cells where a greater amount of area will be anaerobic (more CH_4 is generated in anaerobic versus aerobic areas) and larger landfills tend to generate more CH_4 compared to a smaller landfill (assuming the same waste composition and age of waste). Regarding industrial waste landfills, the WBJ database includes approximately 1,100 landfills accepting industrial and/or construction and demolition debris for 2021 (WBJ 2021). Only 169 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) in the first year (2011) of EPA's Greenhouse Gas Reporting Program for this subpart (GHGRP codified in 40 CFR Part 98), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP. Less industrial waste landfills meet the GHGRP eligibility threshold because they typically accept waste streams with low to no organic content, which will not decompose and generate CH_4 when disposed.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000, then decreased by 11 percent to 202 MMT in 2010, and then increased by 7 percent to approximately 217 MMT in 2022 (see Annex 3.14, Table A-233). Emissions decreased between 1990 to 2022 largely because of increased use of landfill gas collection and control systems, closure of older landfills, better management practices, and increased diversion of organics through state and local policy and regulations. The total amount of MSW generated is expected to increase as the U.S. population continues to grow. The impacts of the coronavirus (COVID-19) pandemic with respect to landfilled waste cannot be quantified as data sources such as the EPA's *Advancing Sustainable Materials Management: Facts and Figures* report have not been published for 2019 through 2022. The quantities of waste landfilled for 2019 to 2022 (presented in Annex 3.14) are extrapolated based on population growth and the last national assessment of MSW landfilled from 2013 (EREF 2016). Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 11.0 MMT in 2022 (see Annex 3.14, Table A-219). CH_4 emissions from industrial waste landfills have also remained at similar levels recently, ranging from 16.1 MMT CO_2 Eq. in 2005 to 18.9 MMT CO_2 Eq. in 2022 when accounting for both CH_4 generation and oxidation. The EPA has focused the industrial waste landfills source category on industrial sectors known to generate and dispose of by-products that are organic and contribute to CH_4 generation, which are the pulp and paper and food processing sectors. Construction and demolition (C&D) landfills, another type of industrial waste landfill, may accept waste that could degrade (e.g., treated wood), but these waste streams are unlikely to generate significant amounts of CH_4 and are therefore not as relevant to the purpose of national greenhouse gas emissions estimate. There is also a general lack of data on annual quantities of waste disposed in industrial waste

landfills, and the GHGRP Subpart TT (Industrial Waste Landfills) dataset has confirmed C&D landfills, for example, are insignificant CH_4 generators.

EPA's Landfill Methane Outreach Program (LMOP) collects information on landfill gas energy projects currently operational or under construction throughout the United States. LMOP's Landfill and Landfill Gas Energy Database contains certain information on the gas collection and control systems in place at landfills provided by organizations that are a part of the program, which can include the amount of landfill gas collected and flared. In 2022, LMOP identified 9 new landfill gas-to-energy (LFGE) projects (EPA 2023b) that began operation.

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
MSW CH_4 Generation[a]	230.0	303.7	332.0	340.9	340.9	335.9	331.4
Industrial CH_4 Generation	13.6	17.9	20.8	20.9	21.0	21.0	21.0
MSW CH_4 Recovered[a]	(23.8)	(148.4)	(195.2)	(201.4)	(206.3)	(203.3)	(199.8)
MSW CH_4 Oxidized[a]	(20.6)	(23.6)	(29.2)	(29.6)	(29.4)	(29.5)	(30.7)
Industrial CH_4 Oxidized	(1.4)	(1.8)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
MSW net CH_4 Emissions	185.5	131.6	107.7	109.9	105.2	103.1	100.9
Industrial CH_4 Emissions[b]	12.2	16.1	18.7	18.8	18.9	18.9	18.9
Total	**197.8**	**147.7**	**126.3**	**128.7**	**124.1**	**122.0**	**119.8**

[a] For years 1990 to 2004, the *Inventory* methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2022, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2023a).

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 7-4: CH_4 Emissions from Landfills (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
MSW CH_4 Generation[a]	8,214	10,845	11,857	12,175	12,174	11,997	11,834
Industrial CH_4 Generation	484	638	741	745	748	750	750
MSW CH_4 Recovered[a]	(851)	(5,301)	(6,970)	(7,193)	(7,367)	(7,262)	(7,135)
MSW CH_4 Oxidized[a]	(736)	(843)	(1,041)	(1,058)	(1,050)	(1,052)	(1,097)
Industrial CH_4 Oxidized	(48)	(64)	(74)	(75)	(75)	(75)	(75)
MSW net CH_4 Emissions	6,627	4,701	3,845	3,924	3,757	3,683	3,602
Industrial net CH_4 Emissions[b]	436	574	667	671	674	675	675
Total	**7,063**	**5,275**	**4,512**	**4,595**	**4,431**	**4,359**	**4,277**

[a] For years 1990 to 2004, the *Inventory* methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2022, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2023a).

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Methodology Applied for MSW Landfills

A combination of IPCC Tier 2 and 3 approaches (IPCC 2006) are used over the reported time series to calculate emissions from MSW Landfills, using two primary methods in accordance with IPCC methodological decision trees based on available data. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below.

Equation 7-1: Landfill Methane Generation

$$\mathrm{CH}_{4,\mathrm{MSW}} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,MSW}$	=	Net CH_4 emissions from solid waste
$G_{CH4,MSW}$	=	CH_4 generation from MSW landfills, using emission factors for DOC, k, MCF, F from IPCC (2006) and other peer-reviewed sources
R	=	CH_4 recovered and combusted
Ox	=	CH_4 oxidized from MSW landfills before release to the atmosphere, using Ox values from IPCC (2006) and other peer-reviewed or scientifically validated literature (40 CFR Part 98)

The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in 40 CFR Part 98.343. The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

The current *Inventory* uses both methods to estimate CH_4 emissions across the time series within EPA's Waste Model, as summarized in Figure 7-3 below. This chapter provides a summary of the methods, activity data, and parameters used. Additional stepwise explanations to generate the net emissions are provided in Annex 3.14.

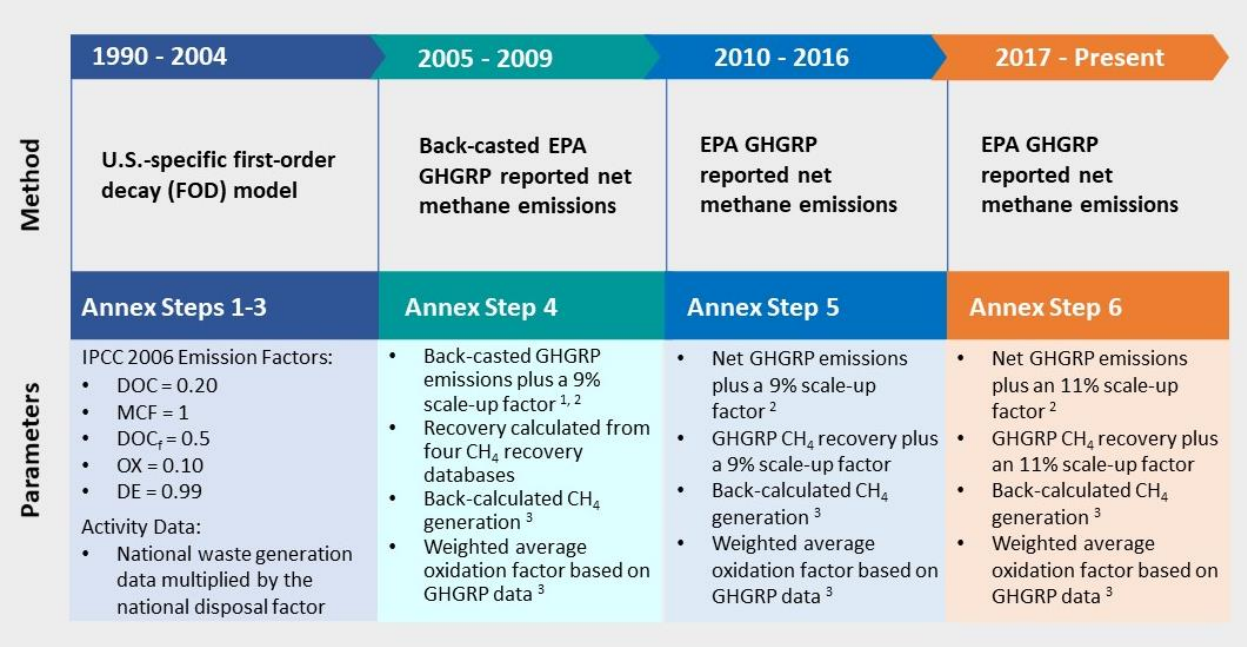
Equation 7-2: Net Methane Emissions from MSW Landfills

$$\mathrm{CH}_{4,\mathrm{Solid\ Waste}} = [\left(\frac{R}{CE\ x\ f_{REC}} - R\right) x(1 - OX) + R\ x\ \left(1 - (DE\ x\ f_{Dest})\right)]$$

where,

$CH_{4,Solid\ Waste}$	=	Net CH_4 emissions from solid waste
R	=	Quantity of recovered CH_4 from Equation HH-4 of EPA's GHGRP
CE	=	Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used (percent)
f_{REC}	=	fraction of hours the recovery system was operating (percent)
OX	=	oxidation factor (percent)
DE	=	destruction efficiency (percent)
f_{Dest}	=	fraction of hours the destruction device was operating (fraction)

Figure 7-3: Methodologies Used Across the Time Series to Compile the U.S. Inventory of Emission Estimates for MSW Landfills



[1] The intent of the scale-up factor is to estimate emissions from landfills that do not report to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. The back-casted emissions are calculated using directly reported net methane emissions for GHGRP reporting years 2010 to 2016. The back-casted emissions are subject to change in each *Inventory* based on new reporting year reports and resubmitted greenhouse gas reports for previous years. This method is compatible with the *2006 IPCC Guidelines* because facilities reporting to the GHGRP either use the FOD method, or directly measured methane recovery data with default emission factors either directly included in the *2006 IPCC Guidelines* or scientifically validated through peer review.

[2] Emission factors used by facilities reporting to GHGRP Subpart HH are facility-specific defaults derived from peer-reviewed literature and the *2006 IPCC Guidelines*.

[3] Methane generation is back-calculated from the net MSW emissions, estimated methane recovery data, and the weighted average oxidation factor based on GHGRP Subpart HH reported data of 0.18 between 2010 to 2016, and 0.21 between 2017 to 2020, and 0.23 in 2021 and 2022.

The Waste Model is a spreadsheet developed by the IPCC for purposes of estimating methane emissions from solid waste disposal sites, adapted to the United States by the inclusion and usage of U.S.-specific parameters. The Waste Model contains activity and waste generation information from both the MSW and Industrial landfill sectors and estimates the amount of CH_4 emissions from each sector for each year of the time series, using both methods. Prior to the 1990 through 2015 *Inventory*, only the FOD method was used. Methodological changes were made to the 1990 through 2015 *Inventory* to incorporate higher tier data (i.e., CH_4 emissions as directly reported to EPA's GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in Annex 3.14, and a technical memorandum (RTI 2017).

Supporting information, including details on the techniques used to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14.

Methodology Applied for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated using a Tier 2 approach (IPCC 2006) and a tailored (country-specific) IPCC waste model in accordance with IPCC methodological decision trees based on available data. Activity

data used are industrial production data (ERG 2023) for two sectors (pulp and paper manufacturing, and food and beverage manufacturing) to which country-specific default waste disposal factors are applied (a separate disposal factor for each sector). The disposal factors, as described below, are based on scientifically reviewed data, and are the same across the entire time series. The emission factors are based on those recommended by the *2006 IPCC Guidelines* and are the same across the entire time series.

The FOD equation from IPCC (2006) is used via the waste model to estimate methane emissions:

Equation 7-3: Net Methane Emissions from Industrial Waste Landfills

$$\mathrm{CH}_{4,\mathrm{IND}} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,Solid\ Waste}$	=	Net CH_4 emissions from solid waste
$G_{CH4,Ind}$	=	CH_4 generation from industrial waste landfills, using production data multiplied by a disposal factor and emission factors for DOC, k, MCF, F (IPCC 2006)
R	=	CH_4 recovered and combusted (no recovery is assumed for industrial waste landfills)
OX	=	CH_4 oxidized from industrial waste landfills before release to the atmosphere (using the *2006 IPCC Guidelines* value for OX of 0.10)

The activity data used in the emission calculations are production data (e.g., the amount of meat, poultry, vegetables processed; the amount of paper produced) versus disposal data. There are currently no facility-specific data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. Based on this limited information, the *Inventory* methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors, thus estimates of industrial landfill emissions focused on these two sectors.

A waste disposal factor is applied to the annual quantities of key food products generated. A waste disposal factor of 4.86 percent is used for 1990 to 2009 and a factor of 6 percent is used for 2010 to the current year. The 4.86 percent disposal factor is based on available data from a 1993 Report to Congress (EPA 1993). The 6 percent waste disposal factor is derived from recent surveys of the food and beverage industry where approximately 94 percent of food waste generated is repurposed (FWRA 2016). The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14.

Landfill CH_4 recovery is not accounted for in industrial waste landfills and is believed to be minimal based on available data collected under EPA's GHGRP for industrial waste landfills (Subpart TT), which shows that only one of the 167 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2023a). The amount of CH_4 oxidized by the landfill cover at industrial waste landfills is assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Additionally, the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) were reviewed to determine if any revisions were required to emission factors, methodologies, and assumptions underlying emission estimates for all source categories. None of the 2019 Refinements are applicable to the country-specific methodology applied for the landfills source category.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste (MSW) generated in the United States can be managed through a variety of methods. MSW that is not recycled, composted, combusted with energy recovery, or digested is assumed to be landfilled. In addition to these management pathways, waste or excess food from the food manufacturing and processing sector may be disposed through the sewerage network, used for animal feed, land application, donated for human consumption, and rendered or recycled into biofuels in the case of animal by-products, fats, oils and greases.

There have been three main sources for nationwide solid waste management data in the United States that the *Inventory* has used (see Annex 3.14, Box A-3 for comparison of estimates from these data sources):

- The *BioCycle* and Earth Engineering Center of Columbia University's SOG in America surveys [no longer published];
- The EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports; and
- The EREF's *MSW Generation in the United States* reports.

The SOG surveys and, most recently EREF, collected state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. These data sources used a 'bottom-up' method. The survey asked for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown was not available, the survey asked for total tons landfilled. The data were adjusted for imports and exports across state lines so that the principles of mass balance were adhered to for completeness, whereby the amount of waste managed did not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

The EPA *Advancing Sustainable Materials Management: Facts and Figures* report characterizes national post-consumer municipal solid waste (MSW) generation and management using a top-down materials flow (mass balance) methodology. It captures an annual snapshot of MSW generation and management in the United States for specific products. Data are gathered from U.S. Government (e.g., U.S. Census Bureau and U.S. Department of Commerce), state environmental agencies, industry and trade groups, and sampling studies. The materials flow methodology develops MSW waste generation estimates of quantities of MSW products in the marketplace (using product sales and replacement data) and assessing waste generation by component material based on product lifespans. The data are used to estimate tons of materials and products generated, recycled, combusted with energy recovery, managed via other food waste management pathways, or landfilled nationwide. MSW that is not recycled or composted is assumed to be combusted or landfilled, except for wasted food, which uses a different methodology and includes nine different management pathways. The 2018 Facts and Figures Report (EPA 2020) uses a methodology that expanded the number of management pathways to include: animal feed; bio-based materials and/or biochemical processing (i.e., rendering); co-digestion and/or anaerobic digestion; composting/aerobic processes; combustion; donation; land application; landfill; and sewer or wastewater treatment.

In this *Inventory*, emissions from solid waste management are presented separately by waste disposal option, except for recycling of waste materials.

- **Recycling**: Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery and are presented in the stationary combustion chapter in the Energy sector. The emissions estimates for recycling are not called out separately.
- **Landfill Disposal**: Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report.
- **Anaerobic Digestion**: Emissions from anaerobic digesters are presented in three different sections depending on the digester category:
    - Emissions from on-farm digesters are included in the Agriculture sector.
    - Emissions from digesters at wastewater treatment plants are included in the Waste sector, and
    - Emissions from stand-alone digesters are also included in the Waste sector.
- **Waste Incineration**: Emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report because, in the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered.s

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this *Inventory* is not facility-specific modeling and while this approach may over- or underestimate CH_4 generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide.

There is a high degree of uncertainty associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in EPA's GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used.

Uncertainty also exists in the scale-up factors (both 9 percent and 11 percent) applied for years 2005 to 2016 and 2017 to 2022, respectively, and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would add up to the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, many gaps existed in the initial development of this Non-Reporting Landfills Database. Assumptions were made for hundreds of landfills to estimate their waste-in-place and the subsequent scale-up factors. The waste-in-place estimated for each landfill is likely not 100 percent accurate and should be considered a reasonable estimate. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP-reported emissions from 2010 to 2022. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to the scale-up factor and years (emission estimates) the scale-up factor is applied to.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized at MSW landfills. Facilities directly reporting to EPA's GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the *Inventory* for both MSW landfills (those not reporting to the GHGRP and for the years 1990 to 2004 when GHGRP data are not available) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the *Inventory*'s CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2009. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 to 2013 *Inventory* report (two years before the full GHGRP data set started being used for net CH_4 emissions for the *Inventory*). Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. The methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered. Additionally, two databases, the EIA database and flare vendor database, could no longer be updated for the entire time series due to external factors. For example, the EIA database has not been updated since 2006 because the EIA stopped collecting landfill recovery data. The EIA database has, for the most part, been replaced by the GHGRP MSW

landfills database. The flare database was populated annually until 2015, but decreasing, voluntary participation from flare vendors sharing their flare sales data for several years prior to 2015.

To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount produced to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the *Inventory* methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation estimates for industrial waste landfills and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills. The specified probability density functions (PDFs) are assumed to be normal for most activity data and emission factors, and due to lack of data, are based on expert judgement (RTI 2004).

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the many data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**119.8**	**109.9**	**137.2**	**-8%**	**+15%**
MSW	CH_4	100.9	98.8	121.2	-2%	+20%
Industrial	CH_4	18.9	13.1	23.7	-31%	+25%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval. Individual uncertainty factors are applied to activity data and emission factors in the Monte Carlo analysis.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the *Inventory* data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the *Inventory* dataset to ensure they are appropriately collected and are reliable;
- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this *Inventory*, because new data were not added to the recovery databases in this *Inventory* year.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[2] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with several general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. For the MSW Landfills sector, under Subpart HH of the GHGRP, MSW Landfills with gas collection are required to report emissions from their site using both a forward- (using a first order decay model as a basis) and back-calculating (using parameters specific to the landfill itself, such as measured recovery and collection efficiency of the landfill gas) methodology. Details on the forward- and back-calculation approach can be found in Annex 3.14 and 40 CFR Subpart HH of Part 98. Reporters can choose which of these two methodologies they believe best represents the emissions at their landfill and are required to submit that value as their total Subpart HH emissions. Facilities are generally not expected to switch between the two equations each year, as the emissions calculated using each method can vary greatly and can have a significant effect on emission trends for that landfill, and potentially the entire MSW Landfill sector under the GHGRP. Key checks are in place to assure that emissions are trending in a sensible way year over year for each reporting landfill.

[2] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Recalculations Discussion

Revisions to the individual facility reports submitted to EPA's GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. Each *Inventory* year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions. The impact of the revisions to the GHGRP Subpart HH annual greenhouse gas reports resubmitted for 2017 to 2021 slightly decreased total Subpart HH reported net emissions, which decreased net MSW emissions by an average of 0.5 percent. A change in net Subpart HH reported emissions results in the same percentage change in the *Inventory* emissions for that year.

Slight revisions were also made to the food and beverage sector production data for nearly every year of the time series. The production data increased by 1 to 2 MMT per year between 1990 to 2017 and decreased by a few MMT per year between 2019 to 2021. These revisions decreased net emissions from industrial waste landfills by less than 0.1 percent between 1990 to 2010. Emissions increased slightly between 2011 to 2017 (ranging from 0.3 percent in 2011 to a high of 1.3 percent in 2017). The revisions to the production data also slightly increased emissions by an average of 0.6 percent between 2018 to 2021.

The combined changes to the MSW and industrial waste landfills activity data resulted in annual increases ranging from 0.005 percent to 0.01 percent to net emissions between 2005 to 2010. A slight decrease in net emissions is observed between 2011 to 2016 (-0.04 percent to -0.2 percent), and an increase, averaging 0.36 percent of emissions, is observed between 2017 to 2021. A 0.6 percent increase is observed for 2020, and a 0.5 percent increase is observed for 2021. Between 2005 to 2020, on average, the impact or change was very small (less than 0.1 percent).

Planned Improvements

EPA received recommendations from industry stakeholders regarding the DOC values and decay rates (k values) required to be used in the GHGRP calculations. Stakeholders have suggested that newer, more up-to-date default values considering recent trends in the composition of waste disposed in MSW landfills for both k and DOC in the GHGRP should be developed and reflected in the 2005 and later years of the *Inventory*. In response, EPA developed a multivariate analysis using publicly available Subpart HH GHGRP data, solving for optimized DOC and k values across the more than 1,100 landfills reporting to the program. The results of this analysis could help inform a current GHGRP rulemaking (87 FR 36920) where changes could be made to the default DOC and k values contained within Subpart HH, which could then be carried over to the *Inventory* emissions estimates for MSW landfills upon promulgation of any revisions to 40 CFR Part 98. This potential improvement may be long-term.

With respect to the scale-up factor, EPA received comments on revisions made to the scale-up for the 1990 to 2020 *Inventory* from a total waste-in-place approach to a time-based threshold of 50 years. Commenters noted that this time-based threshold approach does not adjust for the non-linearity of methane production of landfill gas. In response, EPA will further investigate how best to account for emissions from MSW landfills that do not report to the GHGRP, including using the FOD model for these landfills based on estimated annual waste disposed for this subset of landfills between 2005 to 2022, reverting to the total waste-in-place approach, or modifying the time-based threshold approach. Any methodological revisions to accounting for emissions from this subset of landfills will be made in the next (1990 to 2023) *Inventory*.

Relatedly, EPA will periodically assess the impact to the waste-in-place and emissions data from GHGRP facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the "off-ramp" provisions (reported less than 15,000 metric tons of CO_2 equivalent emissions for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent emissions for 5 consecutive years). If warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the *Inventory*. EPA considered public comments received on the 1990 through 2019 *Inventory*

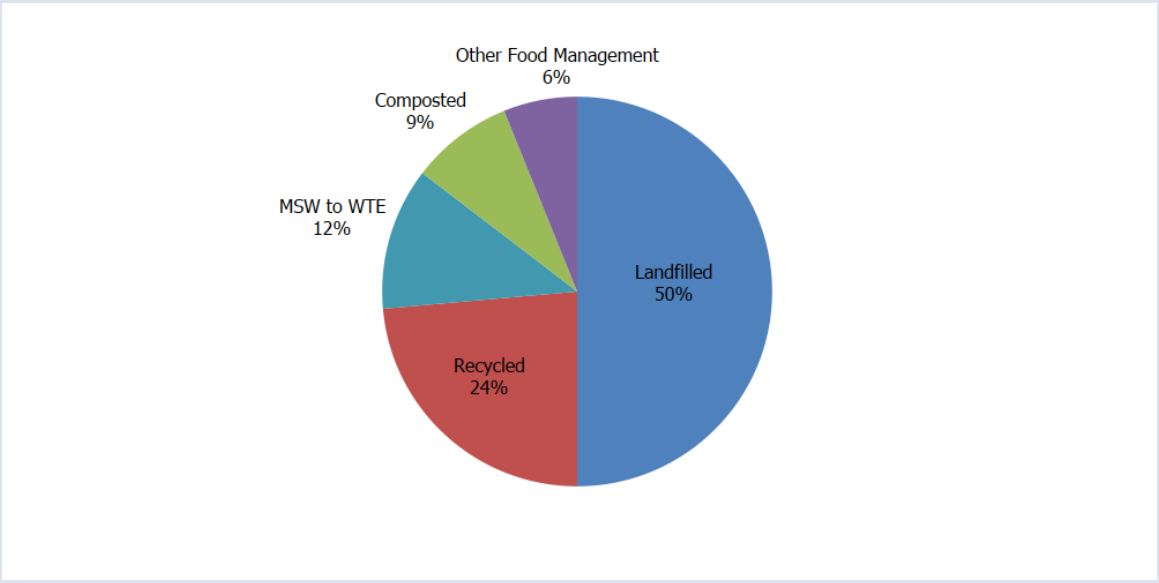
specific to using a time-based threshold to calculate the scale-up factor instead of a total waste-in-place approach. The rationale supporting the comments was that older, closed landfills with large quantities of waste-in-place are driving up the scale-up factor but have little impact on total methane generation. EPA assessed two time-based scenarios for developing the scale-up factor – one scenario looking at the past 30 years of waste disposed, and the second looking at the past 50 years of waste disposed. The 50-year time-based threshold was applied and resulted in the 11 percent scale-up factor used between 2017 and 2022.

EPA is planning to account for unmanaged landfills in Puerto Rico and other U.S. Territories to the landfill emissions estimates. Data limitations for historical waste received at these sites make this challenging. Presently, emissions from managed sites in Puerto Rico and Guam are accounted for in 2005 to present as part of the GHGRP Subpart HH dataset.

Box 7-4: Overview of U.S. Solid Waste Management Trends

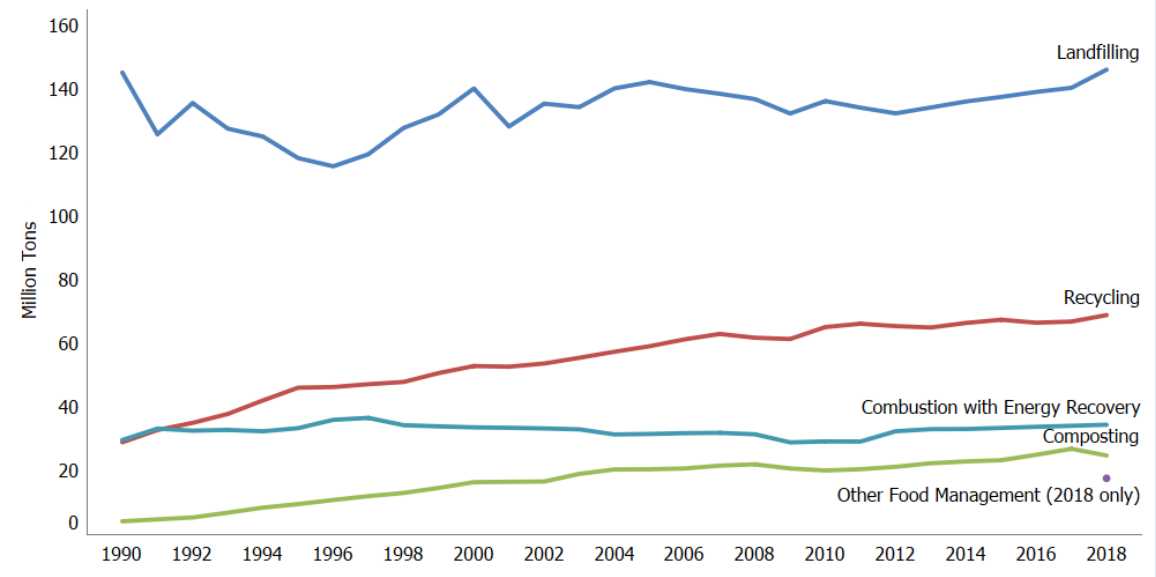
As shown in Figure 7-4 and Figure 7-5 landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-4: Management of Municipal Solid Waste in the United States, 2018



Note: 2018 is the latest year of available data. Data taken from Table 35 of EPA (2020a). MSW to WTE is combustion with energy recovery (WTE = waste-to-energy).
Source: EPA (2020b)

Figure 7-5: MSW Management Trends from 1990 to 2018



Note: 2018 is the latest year of available data. Only one year of data (2018) is available for the "Other Food Management" category.

Source: EPA (2020b). The EPA Advancing Sustainable Materials Management reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA 2020b for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request but are no longer on the EPA's Advancing Sustainable Materials Management web site.[3]

Table 7-6 presents the national-level material composition of waste disposed across typical MSW landfills in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6.

Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-6). As shown in Figure 7-6, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials, although the quantity has been slowly increasing in recent years. Neither Table 7-6 nor Figure 7-6 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

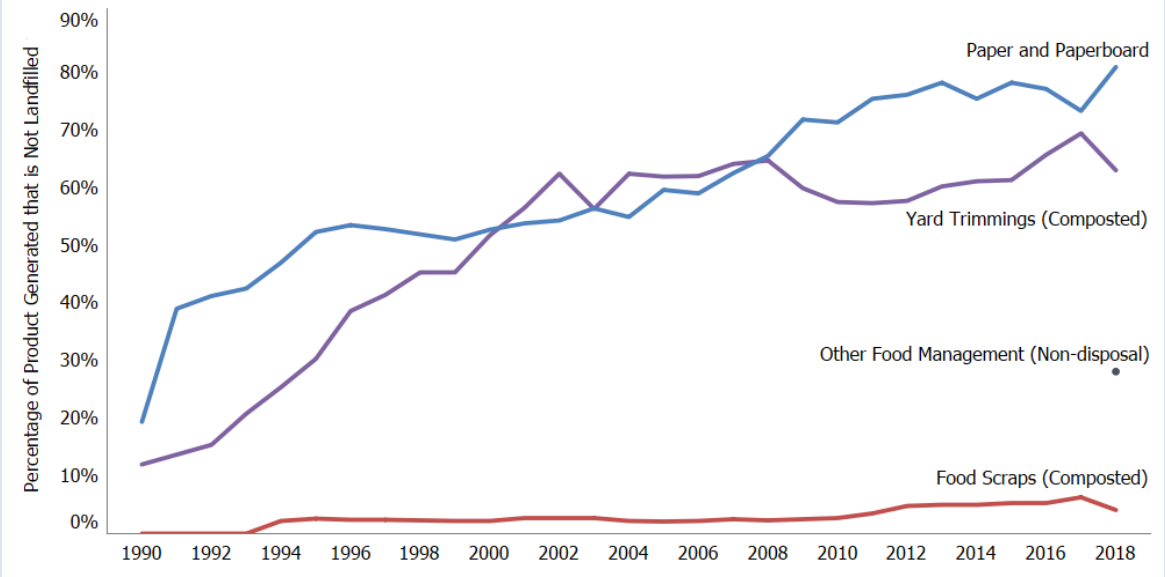
Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2018 (Percent)

Waste Type	1990	2005	2015	2016	2017	2018
Paper and Paperboard	30.0%	24.7%	13.3%	12.7%	13.1%	11.8%
Glass	6.0%	5.8%	5.0%	4.9%	4.9%	5.2%
Metals	7.2%	7.9%	9.5%	9.8%	9.9%	9.5%
Plastics	9.5%	16.4%	18.9%	18.9%	19.2%	18.5%
Rubber and Leather	3.2%	2.9%	3.3%	3.4%	3.5%	3.4%

Textiles	2.9%	5.3%	7.7%	8.0%	8.0%	7.7%
Wood	6.9%	7.5%	8.0%	8.8%	8.7%	8.3%
Other	1.4%	1.8%	2.2%	2.2%	2.2%	2.0%
Food Scraps	13.6%	18.5%	22.0%	22.1%	22.0%	24.1%
Yard Trimmings	17.6%	7.0%	7.8%	6.9%	6.2%	7.2%
Miscellaneous Inorganic Wastes	1.7%	2.2%	2.3%	2.3%	2.3%	2.3%

Source: EPA (2020b)

Figure 7-6: Percent of Degradable Materials Diverted from Landfills from 1990 to 2018 (Percent)



Note: The data shown in this chart are for recycling of paper and paperboard, composting of food scraps and yard trimmings, and alternative management pathways for the Other Food Management (non-disposal) category. The Other Food Management (non-disposal) category is a new addition and only one year of data are available for 2018 (28 percent of the food waste generated was beneficially reused or managed using a method that was not landfilling, recycling, or composting). The Other Food Management pathways include animal feed, bio-based materials/biochemical processing, co-digestion/anaerobic digestion, donation, land application, and sewer/wastewater treatment.

Source: EPA (2020b). The EPA Advancing Sustainable Materials reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA (2020b) for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request, but are not longer on the EPA's Advancing Sustainable Materials Management website.[4]

[3] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

[4] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

7.2 Wastewater Treatment and Discharge (CRT Source Category 5D)

Wastewater treatment and discharge processes are sources of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, nutrients, pathogenic organisms, and chemical contaminants.[5] Treatment of domestic wastewater may either occur on site, most commonly through septic systems, or off site at centralized treatment systems, most commonly at publicly owned treatment works (POTWs). In the United States, approximately 16 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2021a). Treatment of industrial wastewater may occur at the industrial plant using package or specially designed treatment plants or be collected and transferred off site for co-treatment with domestic wastewater in centralized treatment systems.

Centralized Treatment. Centralized wastewater treatment systems use sewer systems to collect and transport wastewater to the treatment plant. Sewer collection systems provide an environment conducive to the formation of CH_4, which can be substantial depending on the configuration and operation of the collection system (Guisasola et al. 2008). Recent research has shown that at least a portion of CH_4 formed within the collection system enters the centralized system where it contributes to CH_4 emissions from the treatment system (Foley et al. 2015).

The treatment plant may include a variety of processes, ranging from physical separation of material that readily settles out (typically referred to as primary treatment), to treatment operations that use biological processes to convert and remove contaminants (typically referred to as secondary treatment), to advanced treatment for removal of targeted pollutants, such as nutrients (typically referred to as tertiary treatment). Not all wastewater treatment plants conduct primary treatment prior to secondary treatment, and not all plants conduct advanced or tertiary treatment (EPA 2010).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. The resulting biomass (sludge) is removed from the wastewater (effluent) prior to discharge to the receiving stream and may be further biodegraded under aerobic or anaerobic conditions, such as anaerobic sludge digestion. Sludge can be produced from both primary and secondary treatment operations. Some wastewater may also be treated using constructed (or semi-natural) wetland systems, though this is much less common in the United States and represents a relatively small portion of wastewater treated centrally (<0.1 percent) (ERG 2016). Constructed wetlands are a coupled anaerobic-aerobic system and may be used as the primary method of wastewater treatment, or are more commonly used as a final treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014). Constructed wetlands do not produce secondary sludge (sewage sludge). Emissions from flooded lands or constructed waterbodies (not used for wastewater treatment) and lands converted to flooded lands (not used for wastewater treatment) are estimated and reported in Chapter 6, under Sections 6.8 Wetlands Remaining Wetlands and 6.9 Lands Converted to Wetlands.

The generation of N_2O may also result from the treatment of wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, proteins, and ammonia in wastewater. Ammonia N is converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic/anaerobic conditions, whereby anaerobic or facultative organisms reduce oxidized forms of nitrogen (e.g.,

[5] Throughout the *Inventory*, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

nitrite, nitrate) in the absence of free oxygen to produce nitrogen gas (N_2). Nitrous oxide is generated as a by-product of nitrification, or as an intermediate product of denitrification. No matter where N_2O is formed it is typically stripped (i.e., transferred from the liquid stream to the air and ultimately emitted to the atmosphere) in aerated parts of the treatment process. Stripping also occurs in non-aerated zones at rates lower than in aerated zones.

On-site Treatment. The vast majority of on-site systems in the United States are septic systems composed of a septic tank, generally buried in the ground, and a soil dispersion system. Solids and dense materials contained in the incoming wastewater (influent) settle in the septic tank as sludge. Floatable material (scum) is also retained in the tank. The sludge that settles on the bottom of the tank undergoes anaerobic digestion. Partially treated water is discharged in the soil dispersal system. The solid fraction accumulates and remains in the tank for several years, during which time it degrades anaerobically. The gas produced from anaerobic sludge digestion (mainly CH_4 and biogenic CO_2) rises to the liquid surface and is typically released through vents. The gas produced in the effluent dispersal system (mainly N_2O and biogenic CO_2) is released through the soil.

Discharge. Dissolved CH_4 and N_2O that is present in wastewater discharges to aquatic environments has the potential to be released into the atmosphere (Short et al. 2014; Short et al. 2017). In addition, the presence of organic matter or nitrogen in wastewater discharges is generally expected to increase CH_4 and N_2O emissions from these aquatic environments. Where organic matter is released to slow-moving aquatic systems, such as lakes, estuaries, and reservoirs, CH_4 emissions are expected to be higher. Similarly, in the case of discharge to nutrient-impacted or hypoxic waters, N_2O emissions can be significantly higher.

In summary, the principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Throughout the rest of this chapter, the term "BOD" refers to BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. Where present, biogas recovery and flaring operations reduce the amount of CH_4 generated that is actually emitted. Per IPCC guidelines (IPCC 2019), emissions from anaerobic sludge digestion, including biogas recovery and flaring operations, where the digester's primary use is for treatment of wastewater treatment solids, are estimated and reported under wastewater treatment. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential. The methods and underlying data sources to estimate emissions from are described in further detail in the "Methodology and Time Series Consistency" section below for treatment of domestic and industrial wastewater.

Overall, treatment of wastewater emitted 42.7 MMT CO_2 Eq. in 2022. Total methane (CH_4) emissions from wastewater treatment and discharge were estimated to be 20.8 MMT CO_2 Eq. (743 kt CH_4). Methane (CH_4) emissions from domestic wastewater treatment and discharge were estimated to be 11.6 MMT CO_2 Eq. (413 kt CH_4) and 2.0 MMT CO_2 Eq. (72 kt CH_4), respectively, totaling 13.6 MMT CO_2 Eq. (485 kt CH_4) in 2022. Emissions remained fairly steady from 1990 through 2002 but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004; U.S. Census Bureau 2021a). In 2022, CH_4 emissions from industrial wastewater treatment and discharge were estimated to be 6.7 MMT CO_2 Eq. (239 kt CH_4) and 0.5 MMT CO_2 Eq. (19 kt CH_4), respectively, totaling 7.2 MMT CO_2 Eq. (258 kt CH_4). Industrial emissions from wastewater treatment have generally increased across the time series through 1999 and then fluctuated up and correspond with production changes from the pulp and paper manufacturing, meat and poultry processing, fruit

and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries. Industrial wastewater emissions have generally seen an uptick since 2016. Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

Nitrous oxide (N_2O) emissions from wastewater treatment and discharge in 2022 totaled 21.9 MMT CO_2 Eq. (83 kt N_2O). In 2022, domestic treatment and discharge were estimated to be 17.0 MMT CO_2 Eq. (64 kt N_2O) and 4.4 MMT CO_2 Eq. (16 kt N_2O), respectively, totaling 21.4 MMT CO_2 Eq. (81 kt N_2O). Domestic emission sources have gradually increased across the time series because of an increasing U.S. population and protein consumption. In 2022, N_2O emissions from industrial wastewater treatment and discharge were estimated to be 0.4 MMT CO_2 Eq. (1.5 kt N_2O) and 0.1 MMT CO_2 Eq. (0.3 kt N_2O), respectively, totaling 0.5 MMT CO_2 Eq. (1.8 kt N_2O). Industrial emission sources have gradually increased across the time series with production changes associated with the treatment of wastewater namely from meat and poultry processing and petroleum refining, but also with contributions from pulp and paper manufacturing and brewery industries. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	**22.7**	**22.7**	**21.4**	**21.1**	**21.0**	**20.7**	**20.8**
Domestic Treatment	15.1	14.6	12.3	11.9	11.7	11.4	11.6
Domestic Effluent	1.4	1.4	2.0	2.0	2.1	2.1	2.0
Industrial Treatment[a]	5.5	6.1	6.5	6.6	6.6	6.7	6.7
Industrial Effluent[a]	0.7	0.6	0.6	0.5	0.5	0.5	0.5
N_2O	**14.8**	**18.1**	**21.2**	**21.6**	**22.3**	**22.1**	**21.9**
Domestic Treatment	10.5	13.7	16.2	16.6	17.2	17.1	17.0
Domestic Effluent	3.9	3.9	4.5	4.5	4.6	4.5	4.4
Industrial Treatment[b]	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Industrial Effluent[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**37.5**	**40.7**	**42.5**	**42.7**	**43.2**	**42.7**	**42.7**

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.
[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.
Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	**811**	**809**	**763**	**755**	**748**	**738**	**743**
Domestic Treatment	539	521	438	426	419	407	413
Domestic Effluent	49	49	73	73	74	74	72
Industrial Treatment[a]	196	216	232	236	236	238	239
Industrial Effluent[a]	27	22	20	19	19	19	19
N_2O	**56**	**68**	**80**	**81**	**84**	**83**	**83**
Domestic Treatment	40	52	61	63	65	65	64
Domestic Effluent	15	15	17	17	17	17	16
Industrial Treatment[b]	1	1	2	2	1	1	1
Industrial Effluent[b]	+	+	+	+	+	+	+

[+] Does not exceed 0.5 kt.
[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.
[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.
Note: Totals by gas may not sum due to independent rounding

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2019) form the basis of the CH_4 and N_2O emission estimates for both domestic and industrial wastewater treatment and discharge.[6] Domestic wastewater treatment follows the IPCC Tier 2 methodology for key pathways, while domestic wastewater discharge follows IPCC Tier 2 discharge methodology and emission factors in accordance with IPCC methodological decision trees based on available data for treatment and discharge. Default factors from IPCC (2019) or IPCC (2006) are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor, though IPCC default factors are often based in part on data from or representative of U.S. wastewater treatment systems. Industrial wastewater treatment follows IPCC Tier 1 and wastewater treatment discharge follows Tier 1 or Tier 2 methodologies, again in accordance with methodological decision trees and available data, depending on the industry. EPA will continue to implement the Tier 2 discharge methodology for more industries as data are investigated and time and resource constraints allow (see the Planned Improvements section below). Similar to domestic wastewater, IPCC default factors are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. In the following cases, the source used to capture activity data changed over the time series. EPA transitioned to these newer data sources to continue estimating emissions in a way that ensured both accuracy and continuity. For example:

- Starch-based ethanol production data: the source used for 1990 to 2017 production was no longer available after 2017. A new, publicly available source was identified and is used for production in 2015-2022. However, this source does not have sufficient data for the earlier timeseries. EPA confirmed with experts familiar with the sources that combining these two sources to populate the time series was accurate (ERG 2019; Lewis 2019) and does not present any significant discontinuities in the time series.
- Brewery production data: the source used for production changed in 2007 to publish craft brewery production broken out by size but does not include data prior to 2007. Therefore, rather than estimating total production data prior to 2007 with this source, another data source was used to ensure accuracy of production data through the time series (ERG 2018b).

Refer to the Recalculations Discussion section below for details on updates implemented to improve accuracy, consistency and/or completeness of the time series.

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems. Within these centralized systems, CH_4 emissions can arise from aerobic systems that liberate dissolved CH_4 that formed within the collection system or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from anaerobic sludge digesters when the captured biogas is not completely combusted. Emissions will also result from the discharge of treated effluent from centralized wastewater plants to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries). The systems with emissions estimates are:

[6] IPCC (2019) updates, supplements, and elaborates the *2006 IPCC Guidelines* where gaps or out-of-date science have been identified. EPA used these methodologies to improve completeness and include sources of greenhouse gas emissions that have not been estimated prior to the 1990 to 2019 *Inventory*, such as N_2O emissions from industrial wastewater treatment, and to improve emission estimates for other sources, such as emissions from wastewater discharge and centralized wastewater treatment.

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C);
- Anaerobic sludge digesters (D); and
- Centralized wastewater treatment effluent (E).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic CH_4 emissions are estimated as follows:

Equation 7-4: Total Domestic CH_4 Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } CH_4 \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D + E$$

Table 7-9 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2022.

Table 7-9: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2022, kt, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (kt)	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems (A)	215	6.0	44.4%
Centrally-Treated Aerobic Systems (B)	77	2.2	15.9%
Centrally-Treated Anaerobic Systems (C)	113	3.2	23.2%
Anaerobic Sludge Digesters (D)	8	0.2	1.7%
Centrally-Treated Wastewater Effluent (E)	72	2.0	14.9%
Total	**485**	**13.6**	**100%**

Notes: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 16 percent in 2022; U.S. Census Bureau 2021a) and an emission factor and then converting the result to kt/year. The method was selected in accordance with IPCC methodological decision trees in based on available data for septic systems.

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2022 and 2023; Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2023). Table 7-10 presents the total U.S. population for 1990 through 2022. The fraction of the U.S. population using septic systems or centralized treatment systems is based on data from the *American Housing Surveys* (U.S. Census Bureau 2021a).

Methane emissions for septic systems are estimated as follows:

Equation 7-5: CH_4 Emissions from Septic Systems

$$Emissions\ from\ Septic\ Systems\ (\mathrm{U.S.\ Specific}) = \mathrm{A}$$
$$= \mathrm{US}_{POP} \times (\mathrm{T}_{SEPTIC}) \times (\mathrm{EF}_{SEPTIC}) \times 1/10^9 \times 365.25$$

Table 7-10: Variables and Data Sources for CH_4 Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
EF_{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH_4/capita/day	1990-2022: Leverenz et al. (2010)
$1/10^9$	Conversion factor	g to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the *Inventory* time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs depend on the total organics in wastewater. Table 7-12 presents the total organically degradable material in wastewater, or TOW, for 1990 through 2022. The TOW was determined using BOD generation rates per capita weighted average both with and without kitchen scraps as well as an estimated percent of housing units that utilize kitchen garbage disposals. Households with garbage disposals (with kitchen scraps or ground up food scraps) typically have wastewater with higher BOD than households without garbage disposals due to increased organic matter contributions (ERG 2018a). The equations are as follows:

Equation 7-6: Total Wastewater BOD5 Produced per Capita (U.S.-Specific [ERG 2018a])

$$\mathrm{BOD}_{\mathrm{gen\ rate}}\ (\mathrm{kg/capita/day}) = \mathrm{BOD}_{\mathrm{without\ scraps}} \times (1 - \%\mathrm{kitchen\ disposal}) + \mathrm{BOD}_{\mathrm{with\ scraps}} \times (\%\mathrm{kitchen\ disposal})$$

Equation 7-7: Total Organically Degradable Material in Domestic Wastewater (IPCC 2019 [Eq. 6.3])

$$\text{TOW}\left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{US}_{POP} \times \text{BOD}_{gen\ rate} \times 365.25 \times \frac{1}{10^6}$$

Table 7-11: Variables and Data Sources for Organics in Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
$BOD_{gen\ rate}$	Total wastewater BOD produced per capita	kg/capita/day	1990-2022: Calculated
$BOD_{without\ scrap}$	Wastewater BOD produced per capita without kitchen scraps[a]	kg/capita/day	1990-2003: Metcalf & Eddy (2003) 2004-2013: Linear interpolation 2014-2022: Metcalf & Eddy (2014)
$BOD_{with\ scraps}$	Wastewater BOD produced per capita with kitchen scraps[a]	kg/capita/day	
% kitchen disposal	Percent of housing units with kitchen disposal[a]	%	1990-2013: U.S. Census Bureau (2013) 2014-2022: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2022: Calculated, ERG (2018a)
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
365.25	Conversion factor	Days in a year	Standard conversion
$1/10^6$	Conversion factor	kg to Gg	Standard conversion

[a] Value of activity data varies over the *Inventory* time series.

Table 7-12: U.S. Population (Millions) and Domestic Wastewater TOW (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Population	253	300	330	332	335	336	337
TOW	8,131	9,624	9,958	10,019	10,132	10,163	10,216

Sources: U.S. Census Bureau (2002); U.S. Census Bureau (2011); U.S. Census Bureau (2021b and 2022); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2023); ERG (2018a).

Methane emissions from POTWs were estimated by multiplying the total organics in centrally treated wastewater (total BOD_5) produced per capita in the United States by the percent of wastewater treated centrally, or percent collected (about 84 percent in 2022), the correction factor for additional industrial BOD discharged to the sewer system, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands),

constructed wetlands only, and anaerobic systems, and the emission factor[7] for aerobic systems, constructed wetlands only, and anaerobic systems. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

In the United States, the removal of sludge[8] from wastewater reduces the biochemical oxygen demand of the wastewater that undergoes aerobic treatment. The amount of this reduction (S) is estimated using the default IPCC (2019) methodology and multiplying the amount of sludge removed from wastewater treatment in the United States by the default factors in IPCC (2019) to estimate the amount of BOD removed based on whether the treatment system has primary treatment with no anaerobic sludge digestion (assumed to be zero by expert judgment), primary treatment with anaerobic sludge digestion, or secondary treatment without primary treatment. The organic component removed from anaerobic wastewater treatment and the amount of CH_4 recovered or flared from both aerobic and anaerobic wastewater treatment were set equal to the IPCC default of zero.

The methodological equations for CH_4 emissions from aerobic and anaerobic systems are:

Equation 7-8: Total Domestic CH_4 Emissions from Centrally Treated Aerobic Systems

$$Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (other\ than\ Constructed\ Wetlands)(B1) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ Only)(B2) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ used\ as\ Tertiary\ Treatment)(B3) = B$$

where,

Equation 7-9: Total Organics in Centralized Wastewater Treatment [IPCC 2019 (Eq. 6.3A)]

$$TOW_{CENTRALIZED}\left(\frac{\text{Gg BOD}}{\text{year}}\right) = \text{TOW} \times \text{T}_{\text{CENTRALIZED}} \times \text{I}_{\text{COLLECTED}}$$

Table 7-13: Variables and Data Sources for Organics in Centralized Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
Centrally Treated Organics (Gg BOD/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/capita/year	1990-2022: Calculated, ERG (2018a)
$T_{CENTRALIZED}$	Percent collected[a]	%	1990-2019: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2020-2022: Forecasted from the rest of the time series
$I_{COLLECTED}$	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2022: IPCC (2019) Eq. 6.3a

[7] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of domestic wastewater (B_0, 0.6 kg CH_4/kg BOD) and the appropriate methane correction factors (MCF) for aerobic (0.03) and anaerobic (0.8) systems (IPCC 2019, Table 6.3) and constructed wetlands (0.4) (IPCC 2014, Table 6.4).

[8] Throughout this document, the term "sludge" refers to the solids separated during the treatment of municipal wastewater. The definition includes domestic septage. "Biosolids" refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal.

[a] Value of this activity data varies over the time series.

Equation 7-10: Organic Component Removed from Aerobic Wastewater Treatment (IPCC 2019 [Eq. 6.3B])

$$S_{aerobic}\left(\frac{Gg}{year}\right) = S_{mass} \times \left[\left(\%\ aerobic \frac{w}{primary} \times K_{rem,aer_{prim}}\right) + \left(\%\ aerobic \frac{w}{out} primary \times K_{rem,aer_{noprim}}\right) + \left(\%aerobic + digestion \times K_{rem,aer_{digest}}\right)\right] \times 1000$$

Equation 7-11: CH_4 Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.1])

$$B1(kt\ CH_4/year) = [(TOW_{CENTRALIZED}) \times (\%\ aerobic_{OTCW}) - S_{aerobic}] \times EF_{aerobic} - R_{aerobic}$$

Table 7-14: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH_4/year)			
$S_{aerobic}$	Organic component removed from aerobic wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
S_{mass}	Raw sludge removed from wastewater treatment as dry mass[a]	Tg dry weight/year	1988: EPA (1993c); EPA (1999) 1990-1995: Calculated based on sewage sludge production change per year EPA (1993c); EPA (1999); Beecher et al. (2007) 1996: EPA (1999) 2004: Beecher et al. (2007) Data for intervening years obtained by linear interpolation 2005-2017: Interpolated 2018: NEBRA (2022), as described in ERG (2023) 2019-2022: Forecasted from the rest of the time series. Methodology for estimating sludge generated from the U.S. territories provided in ERG (2023).
% $aerobic_{OTCW}$	Percent of flow to aerobic systems, other than wetlands[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
% aerobic w/primary	Percent of aerobic systems with primary treatment and no anaerobic sludge digestion (0)	%	
% aerobic w/out primary	Percent of aerobic systems without primary treatment[a]	%	
%aerobic+digestion	Percent of aerobic systems with primary and anaerobic sludge digestion[a]	%	
K_{rem,aer_prim}	Sludge removal factor for aerobic treatment plants with primary treatment (mixed primary and secondary sludge, untreated or treated aerobically) (0.8)	kg BOD/kg sludge	1990-2022: IPCC (2019) Table 6.6a
K_{rem,aer_noprim}	Sludge removal factor for aerobic wastewater treatment plants without separate primary treatment (1.16)	kg BOD/kg sludge	

Variable	Variable Description	Units	Inventory Years: Source of Value
K_{rem,aer_digest}	Sludge removal factor for aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically) (1)	kg BOD/kg sludge	
$EF_{aerobic}$	Emission factor – aerobic systems (0.018)	kg CH_4/kg BOD	1990-2022: IPCC (2019) Table 6.3
$R_{aerobic}$	Amount CH_4 recovered or flared from aerobic wastewater treatment (0)	kg CH_4/year	1990-2022: IPCC (2019) Eq. 6.1
1000	Conversion factor	metric tons to kilograms	Standard conversion

[a] Value of this activity data varies over the time series.

Constructed wetlands provide aerobic treatment but also exhibit partially anaerobic conditions; however, they are referred to in this chapter as aerobic systems. Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. Methane emissions equations from constructed wetlands used as sole treatment were previously described. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

For constructed wetlands, an IPCC default emission factor for surface flow wetlands was used. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A median BOD_5 concentration of 9.1 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. This median value is based on plants generally utilizing simple settling and biological treatment (EPA 2013). Constructed wetlands do not have secondary sludge removal.

Equation 7-12: CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) [IPCC 2014 (Eq. 6.1)]

$$\text{B2}\left(\frac{\text{kt CH}_4}{\text{year}}\right) = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\ \text{aerobic}_{\text{CW}})] \times (EF_{\text{CW}})$$

Equation 7-13: CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S. Specific)

$$\text{B3}\left(\frac{\text{kt CH}_4}{\text{year}}\right) = \left[\left(\text{POTW}_{\text{flow}_{\text{CW}}}\right) \times \left(\text{BOD}_{\text{CW,INF}}\right) \times 3.785 \times (\text{EF}_{\text{CW}})\right] \times \frac{1}{10^6} \times 365.25$$

Table 7-15: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs.[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012)

Variable	Variable Description	Units	Inventory Years: Source of Value
			Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2022: IPCC (2014)
Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH_4/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
$BOD_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (9.1)	mg/L	1990-2022: EPA (2013)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2022: IPCC (2014)
$1/10^6$	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the time series.

Data sources and methodologies for centrally treated anaerobic systems are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-14: CH_4 Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 (Eq. 6.1])

$$C\left(\frac{\text{kt CH}_4}{\text{year}}\right) = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\ \text{anaerobic}) - S_{\text{anaerobic}}] \times EF_{\text{anaerobic}} - R_{\text{anaerobic}}$$

Table 7-16: Variables and Data Sources for CH_4 Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$S_{anaerobic}$	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2022: IPCC (2019) Table 6.3
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0.48)	kg CH_4/kg BOD	

Variable	Variable Description	Units	Inventory Years: Source of Value
$R_{anaerobic}$	Amount CH_4 recovered or flared from anaerobic wastewater treatment (0)	kg CH_4/year	

[a] Value of this activity data varies over the time series.

Emissions from Anaerobic Sludge Digesters:

Total CH_4 emissions from anaerobic sludge digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic sludge digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas, the density of CH_4, one minus the destruction efficiency from burning the biogas in an energy/thermal device and then converting the results to kt/year.

Equation 7-15: CH_4 Emissions from Anaerobic Sludge Digesters (U.S. Specific)

$$\mathrm{D}\left(\frac{\mathrm{kt\ CH_4}}{\mathrm{year}}\right) = \left[\left(\mathrm{POTW_{flow_{AD}}}\right) \times \frac{\mathrm{biogas\ gen}}{100}\right] \times\ 0.0283\ \times\ \left(\mathrm{FRAC_{CH_4}}\right) \times\ 365.25\ \times\ (662) \times\ (1 - \mathrm{DE}) \times \frac{1}{10^9}$$

Table 7-17: Variables and Data Sources for Emissions from Anaerobic Sludge Digesters

Variable	Variable Description	Units	Inventory years: Source of Value
Emissions from Anaerobic Sludge Digesters (kt CH_4/year)			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, and 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
biogas gen	Gas Generation Rate (1.0)	ft^3/capita/day	1990-2022: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2022: Ten-State Standards (2004)
0.0283	Conversion factor	ft^3 to m^3	Standard Conversion
$FRAC_{CH_4}$	Proportion of Methane in Biogas (0.65)	No units	1990-2022: Metcalf & Eddy (2014)
365.25	Conversion factor	Days in a year	Standard conversion
662	Density of Methane (662)	g CH_4/m^3 CH_4	1990-2022: EPA (1993a)
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2022: EPA (1998); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
$1/10^9$	Conversion factor	g to kt	Standard conversion

[a] Value of this activity data varies over the time series.

Emissions from Discharge of Centralized Treatment Effluent:

Methane emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge. The BOD in treated effluent was determined by multiplying the total organics in centrally treated wastewater by the percent of wastewater treated in primary, secondary, and tertiary treatment, and the fraction of organics remaining after primary treatment (one minus the fraction of organics removed from primary treatment, secondary treatment, and tertiary treatment).

Equation 7-16: CH_4 Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$\mathrm{E}\left(\frac{\mathrm{kt\ CH_4}}{\mathrm{year}}\right) = \left(\mathrm{TOW_{RLE}} \times \mathrm{EF_{RLE}}\right) + \left(\mathrm{TOW_{Other}} \times \mathrm{EF_{Other}}\right)$$

where,

Equation 7-17: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.3D])

$$\mathrm{TOW_{EFFtreat,CENTRALIZED}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{primary} \times \left(1 - \mathrm{TOW_{rem,PRIMARY}}\right)\right] + \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{secondary} \times \left(1 - \mathrm{TOW_{rem,SECONDARY}}\right)\right] + \left[\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{tertiary} \times \left(1 - \mathrm{TOW_{rem,TERTIARY}}\right)\right]$$

Equation 7-18: Total Organics in Effluent Discharged to Reservoirs, Lakes, or Estuaries (U.S.-Specific)

$$\mathrm{TOW_{RLE}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{RLE}}$$

Equation 7-19: Total Organics in Effluent Discharged to Other Waterbodies (U.S.-Specific)

$$\mathrm{TOW_{Other}}\left(\frac{\mathrm{Gg\ BOD}}{\mathrm{year}}\right) = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{Other}}$$

Table 7-18: Variables and Data Sources for CH_4 Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$\mathrm{TOW_{EFFtreat,CENTRALIZED}}$	Total organics in centralized treatment effluent[a]	Gg BOD/year	1990-2022: Calculated
$\mathrm{TOW_{CENTRALIZED}}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2022: Calculated
% primary	Percent of primary domestic centralized treatment[a]	%	1990, 1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	
$\mathrm{TOW_{rem,PRIMARY}}$	Fraction of organics removed from primary domestic centralized treatment (0.4)	No units	1990-2022: IPCC (2019) Table 6.6B
$\mathrm{TOW_{rem,SECONDARY}}$	Fraction of organics removed from secondary domestic centralized treatment (0.85)	No units	
$\mathrm{TOW_{rem,TERTIARY}}$	Fraction of organics removed from tertiary domestic centralized treatment (0.90)	No units	
$\mathrm{TOW_{RLE}}$	Total organics in effluent discharged to reservoirs, lakes, and estuaries[a]	Gg BOD/year	1990-2022: Calculated

Variable	Variable Description	Units	Source of Value
TOW_{Other}	Total organics in effluent discharge to other waterbodies[a]	Gg BOD/year	
EF_{RLE}	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114)	kg CH_4/kg BOD	1990-2022: IPCC (2019) Table 6.8
EF_{Other}	Emission factor (discharge to other waterbodies) (0.021)	kg CH_4/kg BOD	
$Percent_{RLE}$	% discharged to reservoirs, lakes, and estuaries[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2022: Set equal to 2012
$Percent_{Other}$	% discharged to other waterbodies[a]	%	

[a] Value of this activity data varies over the time series.

Industrial Wastewater CH_4 Emission Estimates

Industrial wastewater CH_4 emissions originate from on-site treatment systems, typically comprised of biological treatment operations. The collection systems at an industrial plant are not as extensive as domestic wastewater sewer systems; therefore, it is not expected that dissolved CH_4 will form during collection. However, some treatment systems are designed to have anaerobic activity (e.g., anaerobic reactors or lagoons), or may periodically have anaerobic conditions form (facultative lagoons or large stabilization basins). Emissions will also result from discharge of treated effluent to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries).

Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the *Inventory*. The main criteria used to identify U.S. industries likely to generate CH_4 from wastewater treatment are whether an industry generates high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top six industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; petroleum refining; and breweries. Wastewater treatment and discharge emissions for these sectors for 2022 are displayed in Table 7-19 below. Further discussion of wastewater treatment for each industry is included below.

Table 7-19: Total Industrial Wastewater CH_4 Emissions by Sector (2022, MMT CO_2 Eq. and Percent)

Industry	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	5.7	79.0%
Pulp & Paper	0.8	11.6%
Fruit & Vegetables	0.2	3.3%
Ethanol Refineries	0.2	2.3%
Breweries	0.1	2.0%
Petroleum Refineries	0.1	1.7%
Total	**7.2**	**100%**

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

Equation 7-20 presents the general IPCC equation (Equation 6.4, IPCC 2019) to estimate CH_4 emissions from each type of treatment system used for each industrial category.

Equation 7-20: Total CH_4 Emissions from Industrial Wastewater

$$\mathrm{CH_4\ (industrial\ sector)} = [(\mathrm{TOW}_i - \mathrm{S}_i) \times \mathrm{EF} - \mathrm{R}_i]$$

where,

CH_4 (industrial sector)	=	Total CH_4 emissions from industrial sector wastewater treatment (kg/year)
I	=	Industrial sector
TOW_i	=	Total organics in wastewater for industrial sector *i* (kg COD/year)
S_i	=	Organic component removed from aerobic wastewater treatment for industrial sector *i* (kg COD/year)
EF	=	System-specific emission factor (kg CH_4/kg COD)
R_i	=	Methane recovered for industrial sector *i* (kg CH_4/year)

Equation 7-21 presents the general IPCC equation to estimate the total organics in wastewater (TOW) for each industrial category.

Equation 7-21: TOW in Industry Wastewater Treatment Systems

$$\mathrm{TOW}_i = \mathrm{P}_i \times \mathrm{W}_i \times \mathrm{COD}_i$$

where,

TOW_i	=	Total organically degradable material in wastewater for industry *i* (kg COD/yr)
i	=	Industrial sector
P_i	=	Total industrial product for industrial sector *i* (t/yr)
W_i	=	Wastewater outflow (m^3/t product)
COD_i	=	Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m^3)

The annual industry production is shown in Table 7-20, and the average wastewater outflow and the organics loading in the outflow is shown in Table 7-21.

For some industries, U.S.-specific data on organics loading is reported as BOD rather than COD. In those cases, an industry-specific COD:BOD ratio is used to convert the organics loading to COD.

The amount of organics treated in each type of wastewater treatment system was determined using the percent of wastewater in the industry that is treated on site and whether the treatment system is anaerobic, aerobic or partially anaerobic. Table 7-22 presents the industrial wastewater treatment activity data used in the calculations and described in detail in ERG (2008a), ERG (2013a), ERG (2013b), and ERG (2021a). For CH_4 emissions, wastewater treated in anaerobic lagoons or reactors was categorized as "anaerobic", wastewater treated in aerated stabilization basins or facultative lagoons were classified as "ASB" (meaning there may be pockets of anaerobic activity), and wastewater treated in aerobic systems such as activated sludge systems were classified as "aerobic/other."

The amount of organic component removed from aerobic wastewater treatment as a result of sludge removal ($S_{aerobic}$) was either estimated as an industry-specific percent removal, if available, or as an estimate of sludge produced by the treatment system and IPCC default factors for the amount of organic component removed (K_{rem}), using one of the following equations. Table 7-23 presents the sludge variables used for industries with aerobic wastewater treatment operations (i.e., pulp and paper, fruit/vegetable processing, and petroleum refining).

Equation 7-22: Organic Component Removed from Aerobic Wastewater Treatment – Pulp, Paper, and Paperboard

$$S_{pulp,asb} = TOW_{pulp} \times \%\ \text{removal w/primary}$$

where,

$S_{pulp,asb}$ = Organic component removed from pulp and paper wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
TOW_{pulp} = Total organically degradable material in pulp and paper wastewater (Gg COD/yr)
% removal w/primary = Percent reduction of organics in pulp and paper wastewater associated with sludge removal from primary treatment (%)

Equation 7-23: Organic Component Removed from Aerobic Treatment Plants

$$S_{aerobic} = S_{mass} \times K_{rem} \times 10^{-6}$$

where,

$S_{aerobic}$ = Organic component removed from fruit and vegetable or petroleum refining wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
K_{rem} = Sludge factor (kg BOD/kg sludge)
10^{-6} = Conversion factor, kilograms to Gigagrams

Equation 7-24: Raw Sludge Removed from Wastewater Treatment as Dry Mass

$$S_{mass} = (S_{prim} + S_{aer}) \times P \times W$$

where,

S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
S_{prim} = Sludge production from primary sedimentation (kg sludge/m^3)
S_{aer} = Sludge production from secondary aerobic treatment (kg sludge/m^3)
P = Production (t/yr)
W = Wastewater outflow (m^3/t)

Default emission factors[9] from IPCC (2019) were used. Information on methane recovery operations varied by industry. See industry descriptions below.

[9] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of wastewater (B_0, 0.25 kg CH_4/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019), Table 6.3.

Table 7-20: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, Breweries, and Petroleum Refining Production (MMT)

Activity	1990	2005	2018	2019	2020	2021	2022
Pulp and Paper[a]	83.6	92.4	78.7	76.3	74.7	75.5	73.9
Meat (Live Weight Killed)	27.3	31.4	36.4	37.4	37.8	38.1	37.9
Poultry (Live Weight Killed)	14.6	25.1	29.4	30.1	30.5	30.5	31.1
Vegetables, Fruits and Juices	40.8	45.3	42.3	41.8	40.6	39.2	38.4
Ethanol Production	2.5	11.7	48.1	47.1	41.6	44.8	48.3
Breweries	23.9	23.1	21.5	21.1	21.1	21.2	21.6
Petroleum Refining	702.4	818.6	951.7	940	806.5	858.3	892.1

[a] Pulp and paper production is the sum of market pulp production plus paper and paperboard production.

Sources: Pulp and Paper – FAO (2023a) and FAO (2023b); Meat, Poultry, and Fruits and Vegetables – USDA (2023a,2023b, 2023c, 2023d, 2022a, and 2022b), ERG (2023); Ethanol – Cooper (2018) and RFA (2023a and 2023b); Breweries – Beer Institute (2011) and TTB (2022); Petroleum Refining – EIA (2023).

Table 7-21: U.S. Industrial Wastewater Characteristics Data (2022)

Industry	Wastewater Outflow (m^3/ton)	Wastewater BOD (g/L)	Wastewater COD (kg/m^3)	COD:BOD Ratio
Pulp and Paper	See Table 7-25	0.3	--	2.5
Meat Processing	5.3	2.8	--	3
Poultry Processing	12.5	1.5	--	3
Fruit/Vegetable Processing	See Table 7-26		--	1.5
Ethanol Production – Wet Mill	10[a]	1.5	--	2
Ethanol Production – Dry Mill	1.25[a]	3[b]	--	2
Petroleum Refining	0.8	--	0.45	2.5
Breweries – Craft	3.21	--	17.6	1.67
Breweries – NonCraft	1.69	--	17.6	1.67

[a] Units are gallons per gallons ethanol produced.

[b] Units are COD (g/L).

Sources: Pulp and Paper (BOD, COD:BOD) – Malmberg (2018); Meat and Poultry (Outflow, BOD) – ERG (2006a); Meat and Poultry (COD:BOD) – EPA (1997a); Fruit/Vegetables (Outflow, BOD) – CAST (1995), EPA (1974), EPA (1975); Fruit/Vegetables (COD:BOD) – EPA (1997a); Ethanol Production – Wet Mill (Outflow) – Donovan (1996), NRBP (2001), Ruocco (2006b); Ethanol Production – Wet Mill (BOD) – White and Johnson (2003); Ethanol Production – Dry Mill (Outflow and COD) – Merrick (1998), Ruocco (2006a); Ethanol Production (Dry and Wet, COD:BOD) – EPA (1997a); Petroleum Refining (Outflow) – ERG (2013b); Petroleum Refining (COD) – Benyahia et al. (2006); Petroleum Refining (COD:BOD) – EPA (1982); Breweries – Craft BIER (2021); ERG (2018b); Breweries – NonCraft ERG (2018b); Brewers Association (2016a); Breweries (Craft and NonCraft; COD and COD:BOD) – Brewers Association (2016b).

Table 7-22: U.S. Industrial Wastewater Treatment Activity Data

Industry	% Wastewater Treated On-Site	% Treated Anaerobically	% Treated Aerobically	% Treated Aerobically	
				% Treated in ASBs	% Treated in Other Aerobic
Pulp and Paper[b]	60	5.2	75.9	38.5	37.4
Meat Processing	33	33[a]	33	0	33
Poultry Processing	25	25[a]	25	0	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	66.7	0	0
Ethanol Production – Dry Mill	75	75	25	0	0
Petroleum Refining	62.1	0	62.1	23.6	38.5
Breweries – Craft	0.5	0.5	0	0	0
Breweries – NonCraft	100	99	1	0	1

[a] Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.

[b] Remaining onsite treated in other treatment assumed to be non-emissive and not shown here.

Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.

Sources: ERG (2008a, 2008b); ERG (2013a); ERG (2013b); ERG (2021a).

Table 7-23: Sludge Variables for Aerobic Treatment Systems

Variable	Industry		
	Pulp and Paper	Fruit/Vegetable Processing	Petroleum Refining
Organic reduction associated with sludge removal (%)	58		
Sludge Production (kg/m^3)			
Primary Sedimentation		0.15	
Aerobic Treatment		0.096	0.096
Sludge Factor (kg BOD/kg dry mass sludge)			
Aerobic Treatment w/Primary Sedimentation and No Anaerobic Sludge Digestion		0.8	
Aerobic Treatment w/out Primary Sedimentation			1.16

Sources: Organic reduction (pulp) – ERG (2008a); Sludge production – Metcalf & Eddy (2003); Sludge factors – IPCC (2019), Table 6.6a.

Emissions from Discharge of Industrial Wastewater Treatment Effluent:

Methane emissions from discharge of industrial wastewater treatment effluent are estimated via a Tier 1 method for all industries except for pulp, paper, and paperboard in accordance with IPCC methodological decision trees in based on available data for treatment and discharge. Emissions from discharge of pulp, paper, and paperboard treatment effluent is estimated via a Tier 2 method and is described in the industry-specific data section. Tier 1 emissions from effluent are estimated by multiplying the total organic content of the discharged wastewater effluent by an emission factor associated with the discharge:

Equation 7-25: CH_4 Emissions from Industrial Wastewater Treatment Discharge

$$\mathrm{CH_4\ Effluent_{IND}} = \mathrm{TOW_{EFFLUENT,IND}} \times \mathrm{EF_{EFFLUENT}}$$

where,

$CH_4\ Effluent_{IND}$ = CH_4 emissions from industrial wastewater discharge for inventory year (kg CH_4/year)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

$EF_{EFFLUENT}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.028 kg CH_4/kg COD or 0.068 kg CH_4/kg BOD) (IPCC 2019)

The COD or BOD in industrial treated effluent ($TOW_{EFFLUENT,IND}$) was determined by multiplying the total organics in the industry's untreated wastewater that is treated on site by an industry-specific percent removal where available or a more general percent removal based on biological treatment for other industries. Table 7-22 presents the percent of wastewater treated onsite, while Table 7-24 presents the fraction of TOW removed during treatment.

Equation 7-26: TOW in Industrial Wastewater Effluent

$$\mathrm{TOW_{EFFLUENT,IND}} = \mathrm{TOW_{IND}} \times \%\,\mathrm{onsite} \times (1 - \mathrm{TOW_{REM}})$$

where,

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

TOW_{IND} = Total organics in untreated wastewater for industry for inventory year (kg COD/year)

%onsite = Percent of industry wastewater treated on site (%)

TOW_{REM} = Fraction of organics removed during treatment

Table 7-24: Fraction of TOW Removed During Treatment by Industry

Industry	TOW_{REM}	Source
Pulp, Paper, and Paperboard	0.91	Malmberg (2018)
Red Meat and Poultry	0.85	IPCC (2019), Table 6.6b
Fruits and Vegetables	0.85	IPCC (2019), Table 6.6b
Ethanol Production		
Biomethanator Treatment	0.90	ERG (2008a), ERG (2006b)
Other Treatment	0.85	IPCC (2019), Table 6.6b
Petroleum Refining	0.93	Kenari, Sarrafzadeh, and Tavakoli (2010)
Breweries	0.85	IPCC (2019), Table 6.6b

Discussion of Industry-Specific Data:

Pulp, Paper, and Paperboard Manufacturing Wastewater Treatment. Wastewater treatment for the pulp, paper, and paperboard manufacturing (hereinafter referred to as "pulp and paper") industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. About 60 percent of pulp and paper mills have on-site treatment with primary treatment and about half of these also have secondary treatment (ERG 2008). In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Pulp and paper mill wastewater treated using anaerobic ponds or lagoons or unaerated ponds were classified as anaerobic (with an MCF of 0.8). Wastewater flow treated in systems with aerated stabilization basins or facultative lagoons was classified as partially anaerobic (with an MCF of 0.2, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons). Wastewater flow treated in systems with activated sludge systems or similarly aerated biological systems was classified as aerobic.

A time series of CH_4 emissions for 1990 through 2022 was developed based on paper and paperboard production data and market pulp production data. Market pulp production values were available directly for 1998, 2000

through 2003, and 2010 through 2021. Where market pulp data were unavailable, a percent of woodpulp that is market pulp was applied to woodpulp production values from FAOSTAT to estimate market pulp production (FAO 2023a). The percent of woodpulp that is market pulp for 1990 to 1997 was assumed to be the same as 1998, 1999 was interpolated between values for 1998 and 2000, 2000 through 2009 were interpolated between values for 2003 and 2010, and 2022 was forecasted from the rest of the time series. A time series of the overall wastewater outflow in units of cubic meters of wastewater per ton of total production (i.e., market pulp plus woodpulp) is presented in Table 7-25. Data for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for 2005 and 2016 were obtained from the 2018 AF&PA Sustainability Report (AF&PA 2018), data for 2018 were obtained from the 2020 AF&PA Sustainability Report (AF&PA 2020), and data for 2020 were obtained from a 2022 AF&PA sustainability update (AF&PA 2022). Data for intervening years were obtained by linear interpolation, while 2021-2022 were set equal to 2020. The average BOD concentration in raw wastewater was estimated to be 0.4 grams BOD/liter for 1990 to 1998, while 0.3 grams BOD/liter was estimated for 2014 through 2022 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table 7-25: Wastewater Outflow (m^3/ton) for Pulp, Paper, and Paperboard Mills

Wastewater Outflow (m^3/ton)	1990	2005	2018	2019	2020	2021	2022
Pulp and Paper	68	43	40	39	39	39	39

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018), AF&PA (2020); AF&PA (2022)

Pulp, Paper, and Paperboard Wastewater Treatment Effluent. Methane emissions from pulp, paper, and paperboard wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge.

Equation 7-27: CH_4 Emissions from Pulp and Paper Discharge (U.S. Specific)

$$Emissions\ from\ Pulp\ and\ Paper\ Discharge\ \left(\text{U. S. Specific}, \frac{\text{kt CH}_4}{\text{year}}\right)$$
$$= (\text{TOW}_{\text{RLE,pulp}} \times \text{EF}_{\text{RLE}}) + (\text{TOW}_{\text{Other,pulp}} \times \text{EF}_{\text{Other}})$$

Equation 7-28: Total Organics in Pulp and Paper Effluent Discharged to Reservoirs, Lakes, Or Estuaries (U.S. Specific)

$$\text{TOW}_{\text{RLE,pulp}}\ (\frac{\text{Gg BOD}}{\text{year}}) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{RLE,pulp}}$$

Equation 7-29: Total Organics in Pulp and Paper Effluent Discharged to Other Waterbodies (U.S. Specific)

$$\text{TOW}_{\text{Other,pulp}}\ (\frac{\text{Gg BOD}}{\text{year}}) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{Other,pulp}}$$

where,

$TOW_{RLE,pulp}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to reservoirs, lakes, or estuaries (Gg BOD/year)
EF_{RLE}	=	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114 kg CH_4/kg BOD) (IPCC 2019)
$TOW_{Other,pulp}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to other waterbodies (Gg BOD/year)
EF_{Other}	=	Emission factor (discharge to other waterbodies) (0.021 kg CH_4/kg BOD) (IPCC 2019)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in pulp, paper, and paperboard manufacturing wastewater effluent for inventory year (Gg BOD/year)

$Percent_{RLE,pulp}$ = Percent of wastewater effluent discharged to reservoirs, lakes, and estuaries (ERG 2021b)

$Percent_{Other,pulp}$ = Percent of wastewater effluent discharged to other waterbodies (ERG 2021b)

The percent of pulp, paper, and paperboard wastewater treatment effluent routed to reservoirs, lakes, or estuaries (3 percent) and other waterbodies (97 percent) were obtained from discussions with NCASI (ERG 2021b). Data for 2019 were assumed the same as the rest of the time series due to lack of available data. Default emission factors for reservoirs, lakes, and estuaries (0.114 kg CH_4/kg BOD) and other waterbodies (0.021 kg CH_4/kg BOD) were obtained from IPCC (2019).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. Although all meat and poultry processing facilities conduct some sort of treatment on site, about 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems.

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. About half of the operations that treat and discharge wastewater use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Wastewater treated in partially anaerobic systems were assigned the IPCC default emission factor of 0.12 kg CH_4/kg BOD. Outflow and BOD data, presented in Table 7-26, were obtained from CAST (1995) for apples, apricots, asparagus, broccoli, carrots, cauliflower, cucumbers (for pickles), green peas, pineapples, snap beans, and spinach; EPA (1974) for potato and citrus fruit processing; and EPA (1975) for all other commodities.

Table 7-26: Wastewater Outflow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	Organic Content in Untreated Wastewater (g BOD/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	9.85	0.751
Fruit		
Apples	9.08	8.16
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.59	1.226
Grapes (for wine)	2.78	1.831

Sources: CAST (1995); EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises a very small percent of ethanol production in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other sugar or starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement and is more efficient in terms of actual ethanol production (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic sludge digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006b).

About 33 percent of wet milling facilities and 75 percent of dry milling facilities treat their wastewater anaerobically (ERG 2006b). A default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006b). For facilities using biomethanators, approximately 90 percent of BOD is removed during on-site treatment (ERG 2006b, 2008a). For all other facilities, the removal of organics was assumed to be equivalent to secondary treatment systems, or 85 percent (IPCC 2019).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[10] Facilities that reported using non-aerated surface impoundments or other biological treatment units (trickling filter, rotating biological contactor), which have the potential to lead to anaerobic conditions, were assigned the IPCC default emission factor of 0.05 kg CH_4/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m^3/ton (ERG 2013b).

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 8,000 (Brewers Association 2021). This increase has primarily been driven by craft breweries, which have increased by over 250 percent during that period. Craft breweries were defined as breweries producing less than six million barrels of beer per year, and non-craft breweries produce greater than six million barrels. With their large amount of water use and high strength wastewater, breweries generate considerable CH_4 emissions from anaerobic wastewater treatment. However, because many breweries recover their CH_4, their emissions are much lower.

The Alcohol and Tobacco Tax and Trade Bureau (TTB) provides total beer production in barrels per year for different facility size categories from 2007 to 2021 (TTB 2022). Because data were unavailable for 2022, EPA extrapolated from 1990 to 2021 values. For years prior to 2007 where TTB data were not readily available, the Brewers Almanac (Beer Institute 2011) was used, along with an estimated percent of craft and non-craft breweries based on the breakdown of craft and non-craft for the years 2007 through 2020.

To determine the overall amount of wastewater produced, data on water use per unit of production and a wastewater-to-water ratio were used from the Benchmarking Report (Brewers Association 2016a) for both craft and non-craft breweries. Since brewing is a batch process, and different operations have varying organic loads, full-strength brewery wastewater can vary widely on a day-to-day basis. However, the organic content of brewery wastewater does not substantially change between craft and non-craft breweries. Some breweries may collect and discharge high strength wastewater from particular brewing processes (known as "side streaming") to a POTW,

[10] Available online at https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector.

greatly reducing the organics content of the wastewater that is treated on site. Subsequently, the MCF for discharge to a POTW was assumed to be zero (ERG 2018b).

Breweries may treat some or all of their wastewater on site prior to discharge to a POTW or receiving water. On-site treatment operations can include physical treatment (e.g., screening, settling) which are not expected to contribute to CH_4 emissions, or biological treatment, which may include aerobic treatment or pretreatment in anaerobic reactors (ERG 2018b). The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems (IPCC 2006). The amount of CH_4 recovered through anaerobic wastewater treatment was estimated, and a 99 percent destruction efficiency was used (ERG 2018b; Stier J. 2018). Very limited activity data are available on the number of U.S. breweries that are performing side streaming or pretreatment of wastewater prior to discharge.

Domestic Wastewater N_2O Emission Estimates

Domestic wastewater N_2O emissions originate from both septic systems and POTWs. Within these centralized systems, N_2O emissions can result from aerobic systems, including systems like constructed wetlands. Emissions will also result from discharge of centrally treated wastewater to waterbodies with nutrient-impacted/eutrophic conditions. The systems with emission estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C); and
- Centralized wastewater treatment effluent (D).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic N_2O emissions are estimated as follows:

Equation 7-30: Total Domestic N_2O Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } N_2O \text{ Emissions from Wastewater Treatment and Discharge } (\text{kt}) = \text{A} + \text{B} + \text{C} + \text{D}$$

Table 7-27 presents domestic wastewater N_2O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent, in 2022.

Table 7-27: Domestic Wastewater N_2O Emissions from Septic and Centralized Systems (2022, kt, MMT CO_2 Eq. and Percent)

	N_2O Emissions (kt)	N_2O Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater N_2O
Septic Systems	3	0.8	3.6%
Centrally-Treated Aerobic Systems	61	16.3	76.0%
Centrally-Treated Anaerobic Systems	+	+	+
Centrally-Treated Wastewater Effluent	16	4.4	20.4%
Total	**81**	**21.4**	**100%**

+ Does not exceed 0.5 kt, 0.05 MMT CO_2 Eq., or 0.5 percent.
Note: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Nitrous oxide emissions from domestic treatment depend on the nitrogen present, in this case, in the form of protein. Per capita protein consumption (kg protein/person/year) was determined by multiplying per capita annual food availability data and its protein content. Those data are then adjusted using a factor to account for the fraction of protein actually consumed. The methodological equations are:

Equation 7-31: Annual per Capita Protein Supply (U.S. Specific)

$$\text{Protein}_{\text{SUPPLY}}\ (\text{kg/person/year}) = \text{Protein}_{\text{per capita}}/1000 \times 365.25$$

Equation 7-32: Consumed Protein (IPCC 2019 [Eq. 6.10A])

$$\text{Protein}\ (\text{kg/person/year}) = \text{Protein}_{\text{SUPPLY}} \times \text{FPC}$$

Table 7-28: Variables and Data Sources for Protein Consumed

Variable	Variable Description	Units	Inventory Years: Source of Value
Protein			
$\text{Protein}_{\text{SUPPLY}}$	Annual per capita protein supply[a]	kg/person/year	1990-2022: Calculated
$\text{Protein}_{\text{per capita}}$	Daily per capita protein supply[a]	g/person/day	1990-2022: USDA (2015)
1000	Conversion factor	g to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
FPC	Fraction of Protein Consumed[a]	kg protein consumed / kg protein available	1990-2010: USDA (2015) 2011-2020: FAO (2022) and scaling factor 2021-2022: Forecasted from the rest of the time series

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 16 percent in 2022; U.S. Census Bureau 2019), consumed protein per capita (kg protein/person/year), the fraction of N in protein, the correction factor for additional nitrogen from household products, the factor for industrial and commercial co-discharged protein into septic systems, the factor for non-consumed protein added to wastewater and an emission factor and then converting the result to kt/year. The method selected is in accordance with IPCC methodological decision trees and available data. All factors were obtained from IPCC (2019).

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2021b and 2022, Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2023). Table 7-12 presents the total U.S. population for 1990 through 2022. The fraction of the U.S. population using septic systems, as well as centralized treatment systems (see below), is based on data from *American Housing Survey* (U.S. Census Bureau 2021a). The methodological equations are:

Equation 7-33: Total Nitrogen Entering Septic Systems (IPCC 2019 [Eq. 6.10])

$$\text{TN}_{\text{DOM}_{\text{SEPTIC}}}\left(\frac{\text{kg N}}{\text{year}}\right)$$

$$= (\text{US}_{\text{POP}} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON\_septic}} \times \text{F}_{\text{IND-COM\_septic}}$$

Equation 7-34: N_2O Emissions from Septic Systems (IPCC 2019 [Eq. 6.9])

$$A\left(\frac{\text{kt } N_2O}{\text{year}}\right) = TN_{DOM\_SEPTIC} \times (EF_{SEPTIC}) \times 44/28 \times 1/10^6$$

Table 7-29: Variables and Data Sources for N_2O Emissions from Septic System

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Septic Systems			
TN_{DOM_SEPTIC}	Total nitrogen entering septic systems	kg N/year	1990-2022: Calculated
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau 2002; Instituto de Estadísticas de Puerto Rico 2021 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2022: IPCC (2019) Eq. 6.10
N_{HH}	Additional nitrogen from household products (1.17)	No units	1990-2022: IPCC (2019) Table 6.10a
$F_{NON\text{-}CON\_septic}$	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	
$F_{IND\text{-}COM\_septic}$	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	1990-2022: IPCC (2019)
EF_{SEPTIC}	Emission factor, septic systems (0.0045)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8a
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Nitrous oxide emissions from POTWs depend on the total nitrogen entering centralized wastewater treatment. The total nitrogen entering centralized wastewater treatment was estimated by multiplying the U.S. population by the percent of wastewater collected for centralized treatment (about 84 percent in 2022), the consumed protein per capita, the fraction of N in protein, the correction factor for additional N from household products, the factor for industrial and commercial co-discharged protein into wastewater treatment, and the factor for non-consumed protein added to wastewater.

Equation 7-35: Total Nitrogen Entering Centralized Systems (IPCC 2019 [Eq. 10])

$$\mathrm{TN_{DOM_{CENTRAL}}}\left(\frac{\text{kg N}}{\text{year}}\right) = (\mathrm{US_{POP}} \times \mathrm{T_{CENTRALIZED}}) \times \text{Protein} \times \mathrm{F_{NPR}} \times \mathrm{N_{HH}} \times \mathrm{F_{NON-CON}} \times \mathrm{F_{IND-COM}}$$

Table 7-30: Variables and Data Sources for Non-Consumed Protein and Nitrogen Entering Centralized Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021b) 2020-2022: U.S. Census Bureau (2022) U.S. Territories other than Puerto Rico: 1990-2022: U.S. Census Bureau (2023)
$T_{CENTRALIZED}$	Percent collected[a]	%	Odd years from 1989 through 2021: U.S. Census Bureau (2021a) Data for intervening years obtained by linear interpolation 2022: Forecasted from the rest of the time series
Protein	Consumed protein per capita[a]	kg/person/year	1990-2022: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2022: IPCC (2019), Eq. 6.10
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2022: IPCC (2019), Table 6.10a
$F_{NON-CON}$	Factor for U.S. specific non-consumed protein (1.13)	No units	

Variable	Variable Description	Units	Inventory Years: Source of Value
$F_{IND\text{-}COM}$	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	1990-2022: IPCC (2019) Table 6.11

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from POTWs were estimated by multiplying the total nitrogen entering centralized wastewater treatment, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands) and anaerobic systems, aerobic systems with constructed wetlands as the sole treatment, the respective emission factors for aerobic systems and anaerobic systems, and the conversion from N_2 to N_2O.

Table 7-34 presents the data for U.S. population, population served by centralized wastewater treatment plants, available protein, and protein consumed. The methodological equations are:

Equation 7-36: Total Domestic N_2O Emissions from Centrally Treated Aerobic Systems

$$Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (other\ than\ Constructed\ Wetlands)(B1) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ Only)(B2) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ used\ as\ Tertiary\ Treatment)$$

$$(B3) = B\ (kt\ N_2O/year)$$

where,

Equation 7-37: N_2O Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.9])

$$\mathrm{B1\ (kt\ N_2O/year)} = [(\mathrm{TN_{DOM\_CENTRAL}}) \times (\%\ \mathrm{aerobic_{OTCW}})] \times \mathrm{EF_{aerobic}} \times 44/28 \times 1/10^6$$

Table 7-31: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt N_2O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized systems[a]	kg N/year	1990-2022: Calculated
% $aerobic_{OTCW}$	Flow to aerobic systems, other than constructed wetlands only / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$EF_{aerobic}$	U.S.-specific emission factor – aerobic systems (0.015)	kg N_2O-N/kg N	1990-2022: IPCC (2022)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Nitrous oxide emissions from constructed wetlands used as sole treatment include similar data and processes as aerobic systems other than constructed wetlands. See description above. Nitrous oxide emissions from

constructed wetlands used as tertiary treatment were estimated by multiplying the flow to constructed wetlands used as tertiary treatment, wastewater N concentration entering tertiary treatment, constructed wetlands emission factor, and converting to kt/year.

Equation 7-38: N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 [Eq. 6.9])

$$B2\ \left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(TN_{DOM\_CENTRAL}) \times (\%\ \text{aerobic}_{CW})] \times EF_{CW} \times 44/28 \times 1/10^6$$

Equation 7-39: N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.-Specific)

$$B3\ \left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(POTW\_flow\_CW) \times (N_{CW,INF}) \times 3.785 \times (EF_{CW})] \times 1/10^6 \times 365.25$$

Table 7-32: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N_2O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2022: IPCC (2014) Table 6.7
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
Emissions from Constructed Wetlands used as Tertiary Treatment (kt N_2O/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment [a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series

Variable	Variable Description	Units	Inventory Years: Source of Value
$N_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2022: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2022: IPCC (2014) Table 6.7
$1/10^6$	Conversion factor	mg to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Data sources and methodologies are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-40: N_2O Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 [Eq. 6.9])

$$C\left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(TN_{DOM\_CENTRAL}) \times (\%\text{ anaerobic})] \times EF_{anaerobic} \times 44/28 \times 1/10^6$$

Table 7-33: Variables and Data Sources for N_2O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: (EPA 1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2022: Forecasted from the rest of the time series
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8A
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	mg to kg	Standard conversion

[a] Value of this activity data varies over the *Inventory* time series.

Table 7-34: U.S. Population (Millions) Fraction of Population Served by Centralized Wastewater Treatment (percent), Protein Supply (kg/person-year), and Protein Consumed (kg/person-year)

Year	1990	2005	2018	2019	2020	2021	2022
Population	253	300	330	332	335	336	337
Centralized WWT Population (%)	75.6	78.8	82.9	83.6	84.2	84.8	83.6
Protein Supply	43.1	44.9	45.5	46	46.9	46.3	46.3
Protein Consumed	33.2	34.7	35.1	35.5	36.2	35.7	35.7

Sources: Population – U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau (2021b); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2022); U.S. Census Bureau (2023); WWTP Population – U.S. Census Bureau (2021a); Available Protein – USDA (2015), FAO (2022); Protein Consumed – FAO (2022).

Emissions from Discharge of Centralized Treatment Effluent:

Nitrous oxide emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total nitrogen in centrally treated wastewater effluent by the percent of wastewater treated in primary, secondary, and tertiary treatment and the fraction of nitrogen remaining after primary, secondary, or tertiary treatment and then multiplying by the percent of wastewater volume routed to waterbodies with nutrient-impaired/eutrophic conditions and all other waterbodies (ERG 2021a) and emission factors for discharge to impaired waterbodies and other waterbodies from IPCC (2019). The methodological equations are:

Equation 7-41: N_2O Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$D\left(\frac{\text{kt } N_2O}{\text{year}}\right) = [(N_{EFFLUENT,IMP} \times EF_{IMP}) + (N_{EFFLUENT,NONIMP} \times EF_{NONIMP})] \times 44/28 \times 1/10^6$$

where,

Equation 7-42: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.8])

$$N_{EFFLUENT,DOM}\left(\frac{\text{kg N}}{\text{year}}\right)$$

$$= [TN_{DOM\_CENTRAL}[11] \times \%\ \text{primary} \times (1 - N_{rem,PRIMARY})] + [TN_{DOM\_CENTRAL} \times \%\ \text{secondary} \times (1 - N_{rem,SECONDARY})] + [TN_{DOM\_CENTRAL} \times \%\ \text{tertiary} \times (1 - N_{rem,TERTIARY})]$$

Equation 7-43: Total Nitrogen in Effluent Discharged to Impaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,IMP}\ (\text{kg N/year}) = (N_{EFFLUENT,DOM} \times \text{Percent}_{IMP})/1000$$

Equation 7-44: Total Nitrogen in Effluent Discharged to Nonimpaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,NONIMP}\ (\text{kg N year}) = N_{EFFLUENT,DOM} \times \text{Percent}_{NONIMP})/1000$$

Table 7-35: Variables and Data Sources for N_2O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$N_{EFFLUENT,DOM}$	Total organics in centralized treatment effluent[a]	kg N/year	1990-2022: Calculated
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2022: Calculated
1000	Conversion factor	kg to kt	Standard Conversion
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	

[11] See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating $TN_{DOM\_CENTRAL}$.

Variable	Variable Description	Units	Source of Value
			Data for intervening years obtained by linear interpolation. 2013-2022: Forecasted from the rest of the time series
$N_{rem,PRIMARY}$	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2022: IPCC (2019) Table 6.10c
$N_{rem,SECONDARY}$	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
$N_{rem,TERTIARY}$	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	
$N_{EFFLUENT,IMP}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2022: Calculated
$N_{EFFLUENT,NONIMP}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	Emission factor (discharge to impaired waterbodies) (0.19)	kg N_2O-N/kg N	1990-2022: IPCC (2019) Table 6.8a
$EF_{NONIMPr}$	Emissions factor (discharge to nonimpaired waterbodies) (0.005)	kg N_2O-N/kg N	
$Percent_{IMP}$	Percent of wastewater discharged to impaired waterbodies[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2022: Set equal to 2012
$Percent_{NONIMP}$	Percent of wastewater discharged to nonimpaired waterbodies[a]	%	

[a] Value for this activity data varies over the *Inventory* time series.

Industrial Wastewater N_2O Emission Estimates

Nitrous oxide emission estimates from industrial wastewater are estimated according to the methodology described in the *2019 Refinement*. U.S. industry categories that are likely to produce significant N_2O emissions from wastewater treatment were identified based on whether they generate high volumes of wastewater, whether there is a high nitrogen wastewater load, and whether the wastewater is treated using methods that result in N_2O emissions. The top four industries that meet these criteria and were added to the *Inventory* are meat and poultry processing; petroleum refining; pulp and paper manufacturing; and breweries (ERG 2021a). Wastewater treatment and discharge emissions for these sectors for 2022 are displayed in Table 7-36 below. Table 7-20 contains production data for these industries.

Table 7-36: Total Industrial Wastewater N_2O Emissions by Sector (2022, MMT CO_2 Eq. and Percent)

Industry	N_2O Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater N_2O
Meat & Poultry	0.2	47.3%
Petroleum Refineries	0.1	30.5%
Pulp & Paper	0.1	21.4%
Breweries	+	0.7%
Total	**0.5**	**100%**

+ Does not exceed 0.5 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

More recent research has revealed that emissions from nitrification or nitrification-denitrification processes at wastewater treatment, previously judged to be a minor source, may in fact result in more substantial emissions (IPCC 2019). N_2O is generated as a by-product of nitrification, or as an intermediate product of denitrification. Therefore, N_2O emissions are primarily expected to occur from aerobic treatment systems. To estimate these emissions, the total nitrogen entering aerobic wastewater treatment for each industry must be calculated. Then, the emission factor provided by the *2019 Refinement* is applied to the portion of wastewater that undergoes aerobic treatment.

The total nitrogen that enters each industry's wastewater treatment system is a product of the total amount of industrial product produced, the wastewater generated per unit of product, and the nitrogen expected to be present in each meter cubed of wastewater (IPCC equation 6.13).

Equation 7-45: Total Nitrogen in Industrial Wastewater

$$TN_{INDi} = P_i \times W_i \times TN_i$$

where,

TN_{INDi} = total nitrogen in wastewater for industry *i* for inventory year, kg TN/year
i = industrial sector
P_i = total industrial product for industrial sector *i* for inventory year, t/year
W_i = wastewater generated per unit of production for industrial sector *i* for inventory year, m^3/t product
Tni = total nitrogen in untreated wastewater for industrial sector *i* for inventory year, kg TN/m^3

For the four industries of interest, the total production and the total volume of wastewater generated has already been calculated for CH_4 emissions. For these new N_2O emission estimates, the total nitrogen in the untreated wastewater was determined by multiplying the annual industry production, shown in Table 7-20, by the average wastewater outflow, shown in Table 7-23 and the nitrogen loading in the outflow shown in Table 7-37.

Table 7-37: U.S. Industrial Wastewater Nitrogen Data

Industry	Wastewater Total N (kg N/ m^3)	Source for Total N
Pulp and Paper	0.30[a]	Cabrera (2017)
Meat Processing	0.19	IPCC (2019), Table 6.12
Poultry Processing	0.19	IPCC (2019), Table 6.12
Petroleum Refining	0.051	Kenari et al. (2010)
Breweries – Craft	0.055	IPCC (2019), Table 6.12
Breweries – NonCraft	0.055	IPCC (2019), Table 6.12

[a] Units are kilograms N per air-dried metric ton of production.

Nitrous oxide emissions from industry wastewater treatment are calculated by applying an emission factor to the percent of wastewater (and therefore nitrogen) that undergoes aerobic treatment (IPCC Equation 6.11).

Equation 7-46: N_2O Emissions from Industrial Wastewater Treatment Plants

$$N_2O\ Plants_{IND} = \left[\sum_i \left(T_{i,j} \times EF_{i,j} \times TN_{INDi}\right)\right] \times \frac{44}{28}$$

where,

$N_2O\ Plants_{IND}$ = N_2O emissions from industrial wastewater treatment plants for inventory year, kg N_2O/year
TN_{INDi} = total nitrogen in wastewater from industry *i* for inventory year, kg N/year
$T_{i,j}$ = degree of utilization of treatment/discharge pathway or system *j*, for each industry *i* for inventory year

i	=	industrial sector
j	=	each treatment/discharge pathway or system
$EF_{i,j}$	=	emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N. 0.015 kg N_2O-N/kg N (IPCC 2022)
44/28	=	conversion of kg N_2O-N into kg N_2O

For each industry, the degree of utilization (Ti,j)–the percent of wastewater that undergoes each type of treatment–was previously determined for CH_4 emissions and presented in Table 7-22.

Emissions from Industrial Wastewater Treatment Effluent:

Nitrous oxide emissions from industrial wastewater treatment effluent are estimated by multiplying the total nitrogen content of the discharged wastewater effluent by an emission factor associated with the location of the discharge. Where wastewater is discharged to aquatic environments with nutrient-impacted/eutrophic conditions (i.e., water bodies which are rich in nutrients and very productive in terms of aquatic animal and plant life), or environments where carbon accumulates in sediments such as lakes, reservoirs, and estuaries, the additional organic matter in the discharged wastewater is expected to increase emissions.

Equation 7-47: N_2O Emissions from Industrial Wastewater Treatment Effluent

$$\mathrm{N_2O\ Effluent_{IND}} = \mathrm{N_{EFFLUENT,IND}} \times \mathrm{EF_{EFFLUENT}} \times 44/28$$

where,

$N_2O\ Effluent_{IND}$	=	N_2O emissions from industrial wastewater discharge for inventory year (kg N_2O/year)
$N_{EFFLUENT,IND}$	=	Total nitrogen in industry wastewater effluent discharged to aquatic environments for inventory year (kg N/year)
$EF_{EFFLUENT}$	=	Tier 1 emission factor for wastewater discharged to aquatic environments (0.005 kg N_2O-N/kg N) (IPCC 2019)
44/28	=	Conversion of kg N_2O-N into kg N_2O

The total N in treated effluent was determined through use of a nutrient estimation tool developed by EPA's Office of Water (EPA 2019). The Nutrient Tool uses known nutrient discharge data within defined industrial sectors or subsectors, as reported on Discharge Monitoring Reports, to estimate nutrient discharges for facilities within that sector or subsector that do not have reported nutrient discharges but are likely to discharge nutrients. The estimation considers, within each sector or subsector, elements such as the median nutrient concentration and flow, as well as the percent of facilities within the sector or subsector that have reported discharges. Data from 2018 are available for the pulp, paper, and paperboard, meat and poultry processing, and petroleum refining industries. To complete the time series, an industry-specific percent removal of nitrogen was calculated using the total nitrogen in untreated wastewater. See Table 7-38.

Because data for breweries was not available, the removal of nitrogen was assumed to be equivalent to secondary treatment, or 40 percent (IPCC 2019). The Tier 1 emission factor (0.005 kg N_2O/kg N) from IPCC (2019) was used.

Table 7-38: Industrial Wastewater Nitrogen Discharged in 2018 by Sector (kg N)

Industry	N $Effluent_{IND}$ (kg N)	Industry-Specific N Removal Factor
Meat & Poultry	12,078,919	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries[a]	1,604,878	NA

[a] Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.
NA (Not Available)
Source: ERG (2021a).

Uncertainty

The overall uncertainty associated with both the 2022 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, petroleum refining, and breweries. Uncertainty associated with the parameters used to estimate N_2O emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, petroleum refining, and breweries. Uncertainty associated with centrally treated constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment (ERG 2021b). The specified probability density functions (PDFs) are assumed to be normal for most activity data and emission factors, and due to lack of data, are based on expert judgement (ERG 2021c).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-39. For 2022, methane emissions from wastewater treatment were estimated to be between 14.9 and 27.7 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo stochastic simulations). This indicates a range of approximately 29 percent below to 33 percent above the 2022 emissions estimate of 20.8 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 13.9 and 64.0 MMT CO_2 Eq., which indicates a range of approximately 36 percent below to 192 percent above the 2022 emissions estimate of 21.9 MMT CO_2 Eq.

Table 7-39: Approach 2 Quantitative Uncertainty Estimates for 2022 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**20.8**	**14.9**	**27.7**	**-29%**	**+33%**
Domestic	CH_4	13.6	8.8	19.3	-35%	+42%
Industrial	CH_4	7.2	4.2	11.4	-42%	+57%
Wastewater Treatment	**N_2O**	**21.9**	**13.9**	**64.0**	**-36%**	**+192%**
Domestic	N_2O	21.4	13.0	63.2	-39%	+195%
Industrial	N_2O	0.5	0.5	1.4	-0.7%	+201%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;

- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emission estimates; and
- Compared estimates to previous estimates to identify significant changes.

Calculation-related QC (category-specific, Tier 2) was performed for a portion of the domestic wastewater treatment discharges methodology, which included assessing available activity data to ensure the most complete publicly data set was used and checking historical trends in the data to assist determination of best methodology for filling in the time series for data that are not available annually.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Population data were updated using the same and latest data sources as the state-level emissions inventory to create consistency across *Inventory* estimates. These changes affected the years 2020 and 2021. Protein data were updated to reflect available protein values available for 2018 through 2020 (FAO 2022). Pulp, paper, and paperboard production data were updated to reflect revised values for 2021 (FAO 2023a). Updated red meat production values for 2021, were updated based on revised data (USDA 2023a). Fruits and vegetables production values were updated for the time series (ERG 2022; USDA 2023c). Ethanol production values for 2021 were based on revised data (RFA 2023a; RFA 2023b). Petroleum refining production values for 2021 were revised based on EIA (2023). Updated values for non-craft brewery wastewater generation were included for the years 2015 and 2020, affecting the values for 2016, 2018, 2019, and 2021 (BIER 2021).

Compared to the previous *Inventory* the cumulative effect of all these recalculations had a minor impact on the overall wastewater treatment emission estimates:

- Domestic wastewater treatment and discharge CH_4 emissions decreased on average 0.2 percent over the timeseries, with 1990 through 2019 not changing and the largest decrease of 3.1 percent (0.4MMT CO_2 Eq.) in 2021.
- Domestic wastewater treatment and discharge N_2O emissions increased an average 5.6 percent over the timeseries, with 1990 through 2017 not changing and the largest increase of 6.8 percent (1.4 MMT CO_2 Eq.) in 2020.
- Industrial wastewater treatment and discharge CH_4 emissions decreased on average 0.01 percent over the timeseries, with the smallest decrease of 0.003 percent (0.0 MMT CO_2 Eq.) in 2017 and largest decrease of 0.2 percent (0.01 MMT CO_2 Eq.) in 2020.
- Industrial wastewater treatment and discharge N_2O emissions increase an average 0.02 percent over the timeseries, with the smallest increase of 0.0 percent (0.0 MMT CO_2 Eq.) in 1990 to the largest increase of 0.6 percent (0.003 MMT CO_2 Eq.) in 2021.

Over the time series, the total emissions on average increased by 0.1 percent from the previous *Inventory*. The changes ranged from the smallest increase, 0.0005 percent (0.0002 MMT CO_2 Eq.), in 2017, to the largest decrease, 2.4 percent (1.0 MMT CO_2 Eq.), in 2020.

Planned Improvements

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement them until data are available or identified:

- Continue to investigate anaerobic sludge digester and biogas data compiled by the Water Environment Federation (WEF) in collaboration with other entities as a potential source of updated activity data. Due to lack of these data, the United States continues to use another method for estimating biogas produced. This method uses the standard 100 gallons/capita/day wastewater generation factor for the United States (Ten-State Standards), which EPA believes is reasonable to estimate national emissions. However, based on stakeholder input, some regions of the United States use markedly less water due to water conservation efforts so EPA plans to investigate updated sources for this method as well.
- Investigate additional sources for estimating wastewater volume discharged and discharge location for both domestic and industrial sources. For domestic wastewater, the goal would be to provide additional data points along the time series, while the goal for industrial wastewater would be to update the Tier 1 discharge methodology to a Tier 2 methodology.
- Investigate additional sources for domestic wastewater treatment type in place data.
- Continue to review whether sufficient data exist to develop U.S.-specific CH_4 or N_2O emission factors for domestic wastewater treatment systems, including whether emissions should be differentiated for systems that incorporate biological nutrient removal operations.
- Investigate additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems.
- Evaluate literature provided by expert review commenters for potential inclusion as updates, in particular focusing on the industrial N_2O emission factor for pulp and paper wastewater treatment.
- Evaluate the use of POTW BOD effluent discharge data from ICIS-NPDES.[12] Currently only half of POTWs report organics as BOD_5 so EPA would need to determine a hierarchy of parameters to appropriately sum all loads. Using these data could potentially improve the current methane emission estimates from domestic discharge, or at least provide a comparison to the current method for QA/QC.
- Evaluate the use of POTW N effluent discharge data from ICIS-NPDES. Currently only about 80 percent of POTWs report a form of N so EPA would need to determine an appropriate method to scale to the total POTW population. EPA is aware of a method for industrial sources and plans to determine if this method is appropriate for domestic sources. Using these data could potentially improve the current nitrous oxide emissions estimates from domestic discharge, or at least provide a comparison to the current method for QA/QC.

7.3 Composting (CRT Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Composting reduces the amount of methane-generating waste entering landfills, destroys pathogens in the waste, sequesters carbon, and provides a source of organic matter. Composting can also generate a saleable product and reduce the need for chemical fertilizers when the end product is used as a fertilizer or soil amendment. This source category assumes all composting facilities are commercial, large-scale anaerobic windrow composting facilities with yard trimmings as the main waste stream composted, which aligns with findings from full-scale compost infrastructure survey data published by BioCycle (2017, 2023). Of 200 major food waste composting facilities in the United States, 75 (38 percent) use the windrow method, 45 (23 percent) use the aerated static pile method, and the remainder use other methods. The BioCycle 2023 survey received responses from facilities using aerobic composting methods (e.g., aerated static piles, in-

[12] ICIS-NPDES refers to EPA's Integrated Compliance Information System – National Pollutant Discharge Elimination System.

vessel composting) are operational in the United States, however national estimates of the material processed by these facilities are not readily available; therefore, emissions estimates by composting method are not included in this source category. Residential backyard composting is also not included in this source category.

Composting naturally converts a large fraction of the degradable organic carbon in the waste material into carbon dioxide (CO_2) through aerobic processes without anthropogenic influence. With anthropogenic influences (e.g., at commercial or large on-site composting operations), anaerobic conditions can be created in sections of the compost pile when there is excessive moisture or inadequate aeration (or mixing) of the compost pile, resulting in the formation of methane (CH_4). Methane in aerobic sections of a windrow pile is generally oxidized by microorganisms, which convert the CH_4 to CO_2 emissions. Even though CO_2 emissions are generated, they are not included in net greenhouse gas emissions for composting. Consistent with the *2006 IPCC Guidelines*, net CO_2 flux from carbon stock changes in waste material are estimated and reported under the LULUCF sector. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial carbon content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can also be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the thermophilic and secondary mesophilic stages of composting (Cornell 2007). Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2022, the amount of waste composted in the United States increased from 3,810 kt to 23,042 kt (see Table 7-42). There was some fluctuation in the amount of waste composted between 2006 to 2009 where a peak of 20,063 kt composted was observed in 2008, which decreased to 18,838 kt composted the following year, presumably driven by the economic crisis of 2009 (data not shown). Since 2009, the amount of waste composted has gradually increased, and when comparing 2010 to 2022, a 26 percent increase in waste composted is observed. Emissions of CH_4 and N_2O from composting from 2010 to 2022 have increased by the same percentage.

In 2022, CH_4 emissions from composting (see Table 7-40 and Table 7-41) were 2.6 MMT CO_2 Eq. (92 kt), and N_2O emissions from composting were 1.8 MMT CO_2 Eq. (7 kt), representing consistent emissions trends over the past several years. Composted material primarily includes yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include small-scale backyard composting and agricultural composting mainly due to the lack of consistent and comprehensive national data. Additionally, it is assumed that backyard composting tends to be a more naturally managed process with less chance of generating anaerobic conditions and CH_4 and N_2O emissions. Agricultural composting is accounted for in Chapter 5, Section 5.4 (Agricultural Soil Management) of this *Inventory*, as most agricultural composting operations are assumed to land-apply the resultant compost to soils.

The growth in composting since the 1990s and specifically over the past decade may be attributable to the following factors: (1) the enactment of legislation by state and local governments that discouraged or banned the disposal of yard trimmings and/or food waste in landfills, (2) an increase in yard trimming collection and yard trimming drop off sites operated by local solid waste management districts/divisions, (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure.

Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. Currently, 20 states representing up to 42 percent of the nation's population have enacted legislation banning yard waste from landfill disposal (U.S. Composting Council 2022). Additional initiatives at the metro and municipal level also exist across the United States. Roughly 4,713 composting facilities exist in the United States with most (57.2 percent) composting yard trimmings only (BioCycle 2017).

In the last decade, bans and diversions for food waste have also become more common. As of 2022, eight states (California, Connecticut, Massachusetts, New Jersey, New York, Orgon, Vermont, Washington) and seven local governments (Austin, TX; Boulder, CO; Hennepin County, MN; Portland, OR; New York City, NY; San Francisco, CA; Seattle, WA) had implemented organic waste bans or mandatory recycling laws to help reduce organic waste entering landfills, with most having taken effect after 2013 (U.S. Composting Council 2022). In most cases, organic waste reduction in landfills is accomplished by following recycling guidelines, donating excess food for human consumption, or by sending waste to organics processing facilities (Harvard Law School and CET 2019). An example of an organic waste ban as implemented by California is the California Mandatory Recycling Law (AB1826), which requires companies to comply with organic waste recycling procedures if they produce a certain amount of organic waste and took effect on January 1, 2015 (Harvard Law School and CET 2019). In 2017, *BioCycle* released a report in which 27 of 43 states that responded to their organics recycling survey noted that food waste (collected residential, commercial, institutional, and industrial food waste) was recycled via anaerobic digestion and/or composting. These 27 states reported an estimated total of 1.8 million tons of food waste diverted from landfills in 2016 (BioCycle 2018b). A growing number of initiatives to encourage households and businesses to compost or beneficially reuse food waste also exist.

Table 7-40: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	0.4	2.1	2.5	2.5	2.6	2.6	2.6
N_2O	0.3	1.5	1.8	1.8	1.8	1.8	1.8
Total	**0.7**	**3.6**	**4.3**	**4.3**	**4.4**	**4.4**	**4.4**

Note: Totals may not sum due to independent rounding.

Table 7-41: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4	15	75	90	91	92	92	92
N_2O	1	6	7	7	7	7	7

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-40 and Table 7-41 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006) in accordance with IPCC methodological decision trees and available data. Using this method, emissions are the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

Equation 7-48: Greenhouse Gas Emission Calculation for Composting

$$E_i = M \times EF_i$$

where,

E_i	=	CH_4 or N_2O emissions from composting, kt CH_4 or N_2O
M	=	mass of organic waste composted in kt
EF_i	=	emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006)
i	=	designates either CH_4 or N_2O

Per IPCC Tier 1 methodology defaults, the emission factors for CH_4 and N_2O assume a moisture content of 60 percent in the wet waste (IPCC 2006). While the moisture content of composting feedstock can vary significantly

by type, composting as a process ideally proceeds between 40 to 65 percent moisture (University of Maine 2016; Cornell 1996).

Estimates of the quantity of waste composted (M, wet weight as generated) are presented in Table 7-42 for select years. Estimates of the quantity composted for 1990 and 2005 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2015 (EPA 2018); estimates of the quantities composted for 2017 to 2018 were taken from EPA's *Advancing Sustainable Materials Management: 2018 Tables and Figures* (EPA 2020); the estimate of the quantity composted for 2019 to 2022 were extrapolated using the 2018 quantity composted and a ratio of the U.S. population growth for each year between 2018 and 2022 (U.S. Census Bureau 2021; U.S. Census Bureau 2022; U.S Census Bureau 2023). Estimates of waste composted by commercial facilities in Puerto Rico were provided for select years by EPA Region 2 (Kijanka 2020). This data includes amount of waste composted at three facilities in Puerto Rico for 2017, 2018, and 2019, ranging from approximately 1,200 kt to a high of 15,000 kt. The average waste composted for these years was used as the annual amount composted for the respective facility for years the facility was operational. The annual quantity of composted waste in Puerto Rico was forecasted for 2020, 2021, and 2022 using available data from prior years, assumed metro area population data near where each facility is located, and the Microsoft Excel FORECAST function to obtain annual composting estimates.

Table 7-42: U.S. Waste Composted (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Waste Composted	3,810	18,655	22,594	22,698	22,918	22,946	23,042

Uncertainty

The major uncertainty drivers are the assumption that all composting emissions come from commercial windrow facilities and the use of default emission factors (IPCC 2006) which is tied to a homogenous mixture of waste processed across the country (largely yard trimmings). Data presented by BioCycle (BioCycle 2017, 2023) confirm most composting operations use the windrow method and yard trimmings are the largest share of material composted across the country, but there are other composting methods used and waste characteristics will vary at a facility level. Additionally, there are composting operations in Puerto Rico and U.S. territories that are not explicitly included in the national quantity of material composted as reported in the EPA Sustainable Materials Management Reports because the methodological scope does not include Puerto Rico and U.S. territories. EPA took steps to include emissions from Puerto Rico and U.S. Territories beginning in the 1990 to 2020 *Inventory* and will continue to seek out additional data in future *Inventories*.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±58 percent for the Tier 1 methodology and considers the individual emission factors applied to the default emission factors and activity data.

Emissions from composting in 2022 were estimated to range between 1.8 and 7.0 MMT CO_2 Eq., which indicates a range of 58 percent below to 58 percent above the 2022 emission estimate of each gas (see Table 7-43).

Table 7-43: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4	2.6	1.1	4.1	-58%	+58%
Composting	N_2O	1.8	0.8	2.9	-58%	+58%
Composting	**Total**	**4.4**	**1.8**	**7.0**	**-58%**	**+58%**

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current *Inventory*.

Recalculations Discussion

No recalculations were performed for the 1990 to 2022 *Inventory*.

Planned Improvements

EPA recently completed a literature search on emission factors and composting systems and management techniques that were documented in a draft technical memorandum. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials in the United States to determine whether the emission factors used in the current methodology can be revised or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. In general, there is a lack of facility-specific data on the management techniques and sum of material composted to enable the use of different emission factors. EPA will continue to seek out more detailed data on composting facilities to enable this improvement in the future.

Relatedly, EPA has received comments during previous *Inventory* cycles recommending that calculations for the composting sector be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents. At this time, EPA is not aware of any available datasets which would enable estimations to be performed at this level of granularity. EPA will continue to search for data which could lead to the development of subcategory-specific composting emission factors to be used in future *Inventory* cycles.

EPA will also continue to seek out activity data including processing capacity and years of operation for commercial composting facilities in Puerto Rico (for additional years), Guam, and other U.S. Territories for inclusion in a future *Inventory*.

7.4 Anaerobic Digestion at Biogas Facilities (CRT Source Category 5B2)

Anaerobic digestion is a series of biological processes in the absence of oxygen in which microorganisms break down organic matter, producing biogas and digestate. The biogas primarily consists of CH_4, biogenic CO_2, and trace amounts of other gases such as N_2O (IPCC 2006) and is often combusted to produce heat and power, or further processed into renewable natural gas or for use as a transportation fuel. Digester gas contains approximately 65 percent CH_4 (a normal range is 55 percent to 65 percent) and approximately 35 percent CO_2 (WEF 2012; EPA 1993). Methane emissions may result from a fraction of the biogas that is lost during the process due to leakages and other unexpected events (0 to 10 percent of the amount of CH_4 generated, IPCC 2006), collected biogas that is not completely combusted, and entrained gas bubbles and residual gas potential in the digestate. Carbon dioxide emissions are biogenic in origin and should be reported as an informational item in the Energy Sector (IPCC 2006). Volume 5 Chapter 4 of the *2006 IPCC Guidelines* notes that at biogas plants where unintentional CH_4 emissions are flared, CH_4 emissions are likely to be close to zero.

Anaerobic digesters differ based on the operating temperature, feedstock type and moisture content, and mode of operation. The operating temperature dictates the microbial communities that live in the digester. Mesophilic

microbes are present at temperatures ranging from 85 to 100 degrees Fahrenheit while thermophilic microbes thrive at temperatures ranging from 122 to 140 degrees Fahrenheit (WEF 2012). Digesters may process one or more types of feedstock, including food waste; municipal wastewater solids; livestock manure; industrial wastewater and residuals; fats, oils, and grease; and other types of organic waste streams. Co-digestion (multiple feedstocks) is employed to increase methane production in cases where an organic matter type does not break down easily. In co-digestion, various organic wastes are decomposed in a singular anaerobic digester by using a combination of wastewater solids or manure and food waste from restaurants or food processing industry, a combination of manure and waste from energy crops or crop residues (EPA 2016), or alternative combinations of feedstock. The moisture content of the feedstock (wet or dry) impacts the amount of biogas generation. Wet anaerobic digesters process feedstock with a solids content of less than 15 percent while dry anaerobic digesters process feedstock with a solids content greater than 15 percent (EPA 2020). Digesters may also operate in batch or continuous mode, which affects the feedstock loading and removal. Batch anaerobic digesters are manually loaded with feedstock all at once and then manually emptied while continuous anaerobic digesters are continuously loaded and emptied with feedstock (EPA 2020).

The three main categories of anaerobic digestion facilities included in national greenhouse gas inventories include the following:

- Anaerobic digestion at biogas facilities, or stand-alone digesters, can be industry-dedicated digesters that process waste from on industry or industrial facility (typically food of beverage waste from manufacturing), or multi-source digesters that process feedstocks from various sources (e.g., municipal food scraps, manure, food processing waste). Some stand-alone digesters also co-digest other organics such as yard waste.
- On-farm digesters manage organic matter and reduce odor generated by farm animals or crops. On-farm digesters are found mainly at dairy, swine, and poultry farms where there is the highest potential for methane production to energy conversion. On-farm digesters may also accept food waste as feedstock for co-digestion.
- Digesters at water resource recovery facilities (WRRF) produce biogas through the treatment and reduction of wastewater solids. Some WRRF facilities may also accept and co-digest food waste.

This section focuses on stand-alone anaerobic digestion at biogas facilities. Emissions from on-farm digesters are included Chapter 5 (Agriculture) and AD facilities at WRRFs are included in Section 7.2.

From 1990 to 2022, the estimated amount of waste managed by stand-alone digesters in the United States increased from approximately 988 kt to 11,947 kt, an increase of 1,109 percent. As described in the Uncertainty section, no data sources present the annual amount of waste managed by these facilities prior to 2015 when the EPA began a comprehensive data collection survey. Thus, the emission estimates between 1990 and 2014, and for 2020 to 2022 are general estimates extrapolated from data collected for years 2015 to 2019 via the EPA surveys (EPA 2018, 2019, 2021, and 2023). The steady increase in the amount of waste processed over the time series is likely driven by increasing interest in using biogas produced from waste as a renewable energy source and other organics diversion goals.

In 2022, emissions from stand-alone anaerobic digestion at biogas facilities were approximately 13,380 MT CO_2 Eq. (0.5 kt) (see Table 7-44 and Table 7-45).

Table 7-44: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (MT CO_2 Eq.)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4 Generation	22,129	66,388	186,507	348,699	239,720	267,603	267,603
CH_4 Recovery	(21,023)	(63,069)	(177,182)	(331,264)	(227,734)	(254,223)	(254,223)
CH_4 Emissions	**1,106**	**3,319**	**9,325**	**17,435**	**11,986**	**13,380**	**13,380**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 7-45: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (kt CH_4)

Activity	1990	2005	2018	2019	2020	2021	2022
CH_4 Generation	1	2	7	12	9	10	10
CH_4 Recovery	(1)	(2)	(6)	(12)	(8)	(9)	(9)
CH_4 Emissions	**+**	**+**	**+**	**1**	**+**	**+**	**+**

+ Does not exceed 0.5 kt CH_4.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology

Methane emissions from anaerobic digestion depend on factors such as the type of waste managed, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), aeration during the digestion process, unintentional leakages, and how the biogas generated is used/combusted (e.g., flared, used on-site, used off-site).

The emissions presented in Table 7-44 were estimated using the IPCC default (Tier 1) methodology (Volume 5, Chapter 4, IPCC 2006) given in Equation 7-49 below, which applies a default leakage factor of 5 percent to the CH_4 generated, which is the product of an emission factor and the mass of organic waste processed (Equation 7-50). Only CH_4 emissions are estimated because N_2O emissions are considered negligible (IPCC 2006). Some Tier 2 data are available (annual quantity of waste digested) for the later portion of the time series (2015 and later). The methods were selected in accordance with IPCC methodological decision trees and available data on organic waste processed.

Per the *2006 IPCC Guidelines*, emissions of CH_4 from anaerobic digestion facilities due to unintentional leakages during process disturbances or other unexpected events are generally between 0 to 10 percent of the amount of CH_4 generated. When facility-specific information or data are unavailable, a 5 percent leakage factor is recommended (IPCC 2006).

Equation 7-49: Methane Emissions Calculation for Anaerobic Digestion

$$CH_4\ Emissions = L \times (G_{CH4})$$

where,

CH_4 Emissions = total CH_4 emissions in inventory year, Gg CH_4
L = leakage factor, default assumed 5 percent (IPCC 2006)
G_{CH4} = total CH_4 generation in inventory year, Gg CH_4

Equation 7-50: Methane Generation Calculation for Anaerobic Digestion

$$G_{CH4} = \sum_i (M_i \times EF_i) \times 10^{-3}$$

where,

M_i = mass of organic waste treated by biological treatment type *i*, Gg, see Table 7-46
EF = emission factor for treatment *i*, g CH_4/kg waste treated, 0.8 Mg/Gg CH_4
i = anaerobic digestion

Per IPCC Tier 1 methodology defaults, the emission factor for CH_4 assumes a moisture content of 60 percent in the wet waste (IPCC 2006). Both liquid and solid wastes are processed by stand-alone digesters and the moisture content entering a digester may be higher. One emission factor, 0.8 Mg/Gg CH_4 is applied for the entire time series (IPCC 2006 Volume 5, Chapter 4, Table 4.1).

The annual quantity of waste digested is sourced from EPA surveys of anaerobic digestion facilities (EPA 2018, 2019, 2021, and 2023). The EPA was granted the authority to survey anaerobic digestion facilities that process food waste annually through an Information Collection Request (ICR No. 2533.01). The scope includes stand-alone and

co-digestion facilities (on-farm and water resource recovery facilities [WRRF]). Four reports with survey results have been published to date:

- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results* (EPA 2018)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results* (EPA 2019)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2017 & 2018): Survey Results* (EPA 2021)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2019): Survey Results* (EPA 2023).

These reports present aggregated survey data including the annual quantity of waste processed by digester type (i.e., stand-alone, on-farm, and WRRF); waste types accepted; biogas generation and end use; and more. The amount of waste digested as reported in the survey reports were assumed to be in wet weight; the majority of stand-alone digesters were found to be wet and mesophilic (EPA 2019).

The aggregated data presented in the EPA reports are underestimates of the actual amount of processed waste and biogas produced because (1) surveys rarely achieve a 100 percent response rate and some fraction of facilities in each survey year did not respond to the survey; (2) EPA focused the surveys on facilities that primarily process food waste, although non-food waste quantities processed were also collected and reported; and (3) while the EPA has done due diligence to identify all stand-alone digesters that process food waste, EPA may not have identified all facilities across the United States and its territories.

The annual quantity of waste digested at stand-alone digesters for 1990 to 2014 (only 1990 and 2005 are shown in Table 7-46) was estimated by multiplying the count of estimated operating facilities (as presented in Table 7-47) by the weighted average of waste digested in 2015 to 2019 collected through EPA's survey data (EPA 2018, 2019, 2021, 2023). Masked survey responses of food and non-food waste processed were shared with the *Inventory* team by the EPA team leading the EPA AD Data Collection Surveys. This provided an accurate count of the number of facilities that provided annual quantities of digested waste, which matters for the weighted average. The weighted average applied to the current *Inventory* is calculated as follows for 1990 to 2014:

Equation 7-50: Weighted Average of Waste Processed

$$Weighted\ Average\ Waste\ Processed = \sum_{year} \frac{W_{year} \times Fac_{year}}{Sum\ of\ All\ Fac}$$

where,

year = the year of data for the average waste processed and count of facilities in the numerator

W = total average waste processed in the respective survey year, food and non-food waste (short tons).

Fac = the number of facilities that reported an amount of waste processed in the respective survey year. Note the number of facilities that provided an annual quantity of waste processed data was internally shared and differs from the total number of facilities that responded to the EPA surveys as presented in EPA (2018, 2019, 2021, and 2023).

The number of facilities that reported annual quantities of waste digested to the EPA survey varies by year. The masked data provided by the EPA AD survey data collection team include data for 41, 44, 42, 43, and 18 facilities between 2015 to 2019, respectively. This data was used to calculate the weighted average of waste digested of 239,709 short tons.

Estimates of the quantity of waste digested for 1990 to 2014 are calculated by multiplying the weighted average of waste digested from the masked survey data by the count of operating facilities in each year. This calculation

assumes that each facility operates continuously from the first year of operation for the remainder of the time series. Additional efforts will be made to quantify the number of operating facilities and estimates of the total waste digested by year for future Inventories as described in the Planned Improvements section.

Estimates of the quantity digested for 2015 to 2019 were taken from EPA's AD survey data (EPA 2018, EPA 2019, EPA 2021, and EPA 2023). In the 1990 to 2022 *Inventory*, the quantity of liquid, non-food waste was converted to tons using a general conversion factor of 3.8 lbs/gallon.

The EPA (2023) report provides a significant increase in data granularity for stand-alone digesters compared to earlier reports because food waste processed by the beverage sector is included as tons of food waste processed as opposed to gallons of food waste processed in prior survey years. Detail on the sources and types of the liquid food and non-food waste was not available in the 2015 to 2018 data to reliably convert the data to tons. However, the 2019 data point provides some assurance that using a general conversion factor to convert liquid waste to tons yields a more comprehensive estimate of total waste processed at stand-alone AD facilities.

The estimate of waste digested for 2020 to 2022 were extrapolated using the average of the waste digested from the 2017 to 2019 survey data (EPA 2021, 2023) as a proxy. The average did not include data from 2015 and 2016 because there is a drop in the amount of waste digested by nearly 1 million tons between 2016 and 2017. The quantities digested between 2015 and 2016 are similar, and quantities digested between 2017 and 2018 are similar. The quantity digested for 2019 is nearly twice the amount of prior EPA survey years because food waste from the beverage sector were able to be accurately converted to tons. Estimates for 2020 to 2022 will be updated as future EPA survey reports are published.

Table 7-46: Estimated U.S. Waste Digested (kt) from 1990-2022

Activity	1990	2005	2018	2019	2020	2021	2022
Waste Digested	988	2,964	8,326	15,567	10,702	11,947	11,947

The estimated count of operating facilities is calculated by summing the count of digesters that began operating by year over the time series. The year a digester began operating is sourced from EPA (2021). This assumes all facilities are in operation from their first year of operation throughout the remainder of the time series, including facilities prior to 1990. This is likely an overestimate of facilities operating per year but does not necessarily translate to an overestimate in the amount of waste processed because a weighted average of waste processed for the surveyed facilities is applied to these years. The number of facilities in 1990 to 2014 are directly used in calculating the emissions for those years.

Table 7-47: Estimated Number of Stand-Alone AD Facilities Operating from 1990-2022

Year	1990	2005	2018	2019	2020	2021	2022
Estimated Count of Operational Facilities	4	12	68	68	68	68	68

Uncertainty

The methodology applied for the 1990 to 2014 emissions estimates should be considered a starting point to build on in future years if additional historical data become available. Five years of facility-provided data are available (2015 to 2019) while the rest of the time series is estimated based on an assumption of facility counts and the 2015 to 2019 weighted average annual waste digested as calculated from survey data. The major limitations, and uncertainty drivers in the emissions estimates, are related to the uncertainty in assumptions to ensure completeness across the time series and the limitations in the EPA AD survey data, as described below:

1. The EPA AD surveys (EPA 2018; EPA 2019; EPA 2021; EPA 2023) did not receive a 100 percent response rate, meaning that the survey data represent a portion, albeit the majority, of stand-alone digesters, and annual waste processed. The methodology applied here did not attempt to estimate waste digested by facilities that did not respond to the survey, which likely underestimates the quantity of waste digested and CH_4 emissions.

2. The EPA AD survey data (EPA 2018; EPA 2019) present both food and non-food waste digested. The non-food waste was reported as liquid (gallons) and solid (tons). The quantity of liquid waste managed for 2015 and 2016, which is used as a proxy for 1990 to 2014, was converted to tons using a general conversion factor of 3.8 lbs/gallon. This may slightly over- or underestimate the quantity of waste digested and CH_4 emissions between 1990 to 2018. This conversion was not made by EPA in the survey report (EPA 2018). However, EPA (2021) did convert the liquid waste managed to tons for 2017 and 2018 using the general conversion factor of 3.8 lbs/gallon.
3. The assumption required to estimate the activity data for 1990 to 2014 may overestimate the number of facilities in operation because it assumes that each facility operates from its start year for the entire time series (i.e. facility closures are not taken into account). This introduces a large amount of uncertainty in the estimates compared to years where there is directly reported survey data. It is unclear whether this under- or over-estimates the quantity of waste digested and CH_4 emissions.
4. The most recent EPA AD survey data (EPA 2023) includes waste processed by the beverage sector, which was not presented in prior survey years. No attempts were made to separately estimate and include this waste stream in years prior to 2019 (i.e. the EPA 2023 survey). This means that annual CH_4 estimates for 1990 to 2018 are underestimated.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±54 percent for the Approach 1 methodology.

Emissions from anaerobic digestion at stand-alone biogas facilities in 2022 were estimated to be between 6,175 and 20,586 MT CO_2 Eq., which indicates a range of 54 percent below to 54 percent above the 2022 emission estimate of CH_4 (see Table 7-48). A ±20 percent uncertainty factor is applied to the annual amount of material digested (i.e., the activity data), which was developed with expert judgment (Bronstein 2021). A ±50 percent default uncertainty factor is applied to the CH_4 emission factor (IPCC 2006). Using the IPCC's error propagation equation (Equation 3.1 in IPCC 2006 Volume 1, Chapter 3), the combined uncertainty percentage is ±54 percent.

Table 7-48: Approach 1 Quantitative Uncertainty Estimates for Emissions from Anaerobic Digestion (MT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Anaerobic Digestion at Biogas Facilities	CH_4	13,380	6,175	20,586	-54%	+54%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current *Inventory*.

Recalculations Discussion

For the current *Inventory*, a methodological change was made whereby the CH_4 emissions are considered equal to leakage from the digester network of pipes. A leakage factor of 5 percent as recommended in IPCC 2006 is applied to the CH_4 generation estimate for all years in the time series. This methodological change applies to every year in the time series and significantly reduces annual CH_4 emissions estimates. Previously the EPA AD Survey data of amount of biogas produced at AD facilities was used for the amount of gas recovered, with the remaining gas assumed to be leaked or emitted. This method calculated higher emissions estimates, which showed most of the gas generated at an AD was emitted, instead of used in biogas projects. This was inconsistent with the EPA AD Survey findings that approximately 95 percent of stand-alone AD facilities use some or all biogas onsite and the

IPCC guidance on default leakage from AD facilities. EPA will further investigate the survey data for the biogas produced data point, since it indicates very low gas utilized as compared to this revised methodology.

The weighted average of waste digested was recalculated for the current *Inventory* to incorporate EPA AD survey data from 2017 to 2019. The recalculation increased the weighted average annual waste digested from 216,494 short tons to 272,249 short tons, an approximately 25 percent increase. The weighted average is applied to the estimated count of stand-along digesters operating between 1990 to 2014 and resulted in a 26 percent increase in the amount of waste digested annually.

Additional recalculations were also made for the waste processed in 2019 to 2021. In the previous *Inventory*, the amount of waste processed for 2019 to 2021 was extrapolated based on available survey data. With the publication of survey data for 2019 (EPA 2023), the values for 2019 were replaced and the extrapolation for years 2020 to 2022 were updated. Recalculations for the amount of waste processed resulted in increases of 88 percent in 2019, 30 percent in 2020, and 45 percent in 2021.

Despite the increase of waste processed across the time series, recalculations for this *Inventory* resulted in significant decreases to the emissions estimates as compared to the previous 1990 through 2021 *Inventory*. Emissions estimates were reduced by 93 percent annually between 1990 to 2014, and between 90 to 95 percent between 2015 to 2021. For example, the net emissions estimate in 2021 decreased from 6.1 kt to 0.48 kt. The decrease in emissions is driven by the methodological change described in the first paragraph.

Planned Improvements

EPA will continue to incorporate updated survey data from future EPA AD Data Collection Surveys when the survey data are published. These revisions will change the estimated emissions for 2020 to 2022. Additionally, quality control checks on the default emission factor used to determine CH_4 generation is in process.

EPA will also reassess how best to estimate annual waste processed using proxy data for years between the EPA AD Data Collection Survey reports as needed (e.g., for 2020, 2021, 2022). The methodology described here assumes the same average amount of waste is processed each year for 2020 through 2022.

EPA continues to seek out data sources to confirm the estimated number of operational facilities by year prior to 2015 and consider how best to estimate the quantity of waste processed per year by these facilities with the goal of better estimating the annual quantity of waste digested between 1990 to 2014. Available data will also be compiled where available for facilities that did not directly respond to the EPA AD Data Collection surveys for completeness.

7.5 Waste Incineration (CRT Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the combustion of waste are accounted for in the Energy sector rather than in the Waste sector because almost all combustion of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The combustion of waste in the United States in 2022 resulted in 12.7 MMT CO_2 Eq. of emissions. For more details on emissions from the combustion of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste combustion include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided.

An analysis of the likely level of medical waste incineration emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of inventory reporting under the Paris Agreement and the UNFCCC. More information on this analysis is provided in Annex 5.

Furthermore, an analysis was conducted on the likely level of sewage sludge incineration emissions based on the total amount of sewage sludge generated and assumed percent incineration. Based on assumed amount of sludge incinerated and non-CO_2 factors for solid biomass it was determined that annual greenhouse gas emissions for sewage sludge incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of inventory reporting under the Paris Agreement and the UNFCCC. More information on this analysis is provided in Annex 5.

7.6 Waste Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of precursors to greenhouse gases. The reporting requirements of the Paris Agreement and the UNFCCC[13] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmosphere aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from waste sources for the years 1990 through 2022 are provided in Table 7-49.

Table 7-49: Emissions of NO_x, CO, NMVOC, and SO_2 from Waste (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
NO_x	84	51	73	73	76	76	75
CO	1,028	1,178	1,182	1,182	1,342	1,343	1,343
NMVOCs	870	152	156	157	173	172	172
SO_2	36	20	23	23	33	32	31

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2022 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 7-49, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Emissions Inventory System (EIS) sectors. The EIS sectors are mapped to categories more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC, based on discussions between the EPA *Inventory* and NEI staff (see crosswalk documented in Annex 6.3).[14] EIS sectors mapped to the waste sector categories in this report include: waste disposal and recycling

[13] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

[14] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1

(landfills; publicly owned treatment works; industrial wastewater; treatment, storage, and disposal facilities; waste incineration; and other).[15] As described in the NEI Technical Support Documentation (TSD) (EPA 2023b), emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing. Within the NEI, there is only one EIS sector for waste generating and handling processes, so precursor estimates are aggregated in Table 7-49 for consistency with NEI reporting. Future presentations of this data may disaggregate emissions so it better maps to reporting categories under the Paris Agreement and the UNFCCC.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022, which are described in detail in the NEI's TSD (EPA 2021). No quantitative estimates of uncertainty were calculated for this source category.

source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRT), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.

[15] Precursor emissions from waste incineration were reported in the Energy sector in the previous *Inventory* but are not disaggregated from the Waste sector in this report.

8. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

9. Recalculations and Improvements

Each year, many emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including improving the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006) and its refinements/supplements, which state:

> *"Both methodological changes and refinements over time are an essential part of improving inventory quality. It is good practice to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors."*

When methodological changes have been implemented, the previous *Inventory's* time series (i.e., 1990 to 2021) is assessed and potentially recalculated to reflect the change, per guidance in IPCC (2006, 2019). Changes in historical data are often the result of changes in statistical data supplied by other agencies, and these changes do not necessarily impact the entire time series.

The results of all methodological changes and historical data updates made in the current *Inventory* in calculating CO_2-equivalent U.S. greenhouse gas emissions and sinks are presented in Figure 9-2, while impacts on both total and net emissions by gas are presented in Table 9-1 and Table 9-2. Collectively, these changes resulted in an average annual decrease of 114.8 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.) (1.9 percent) in net total emissions relative to the previously published *Inventory* (i.e., the 1990 to 2021 report) in units of MMT CO_2 Eq.

Figure 9-1: Impacts of Recalculations on Net Emissions

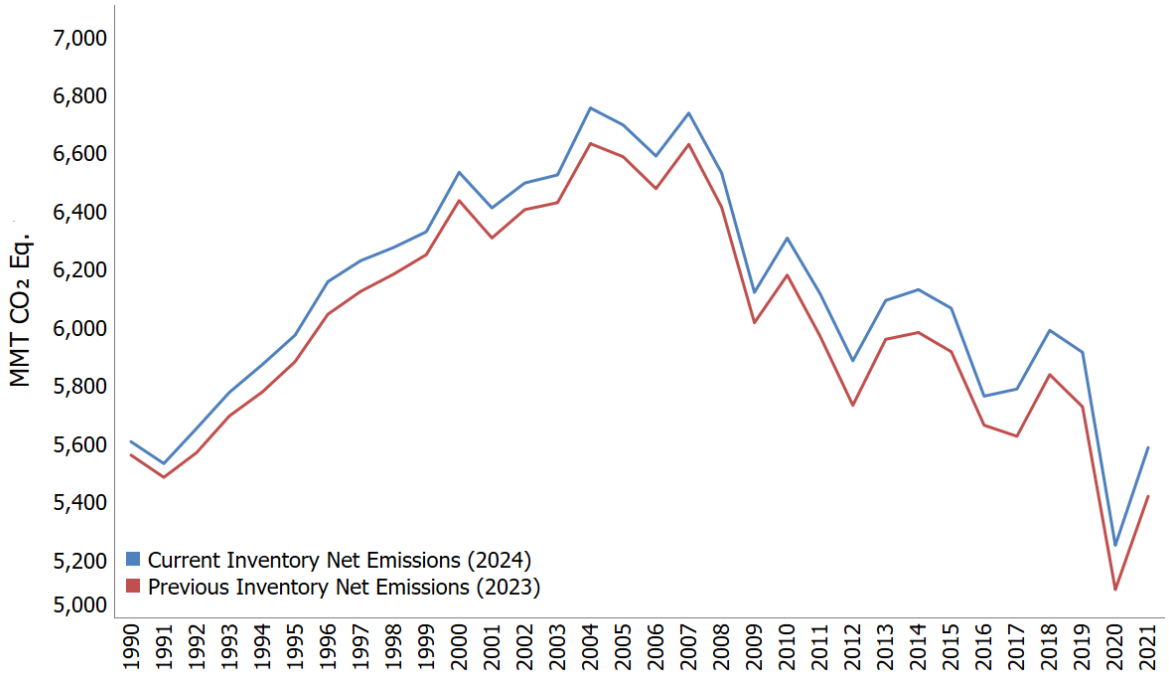


Table 9-1: Overall Impact of Recalculations by Gas Compared to Previous *Inventory*

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
CO_2	10.7	(5.3)	(15.6)	(27.7)	(25.7)	(15.0)	(4.6)
CH_4[a]	3.0	4.4	(2.6)	(13.4)	(6.9)	(7.0)	0.5
N_2O[a]	1.9	3.4	9.3	6.1	2.3	4.9	3.9
HFCs and PFCs	34.0	14.8	6.8	7.2	6.1	5.7	21.2
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Change in LULUCF Total Net Flux[b]	(95.8)	(123.0)	(148.8)	(153.4)	(120.2)	(151.4)	(133.6)
LULUCF Emissions[c]	0.0	(3.5)	(1.6)	(6.2)	(8.0)	(4.9)	(2.2)
CH_4	(0.4)	(2.8)	(1.8)	(4.4)	(6.1)	(3.8)	(2.0)
N_2O	0.4	(0.7)	0.2	(1.8)	(1.9)	(1.1)	(0.2)
Change in LULUCF Sector Net Total[d]	(95.7)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**

[a] Does not include CH_4 and N_2O emissions from LULUCF.

[b] LULUCF carbon stock change includes any C stock gains and losses from all land use and land use conversion categories

[c] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[d] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes. More detail on the impacts of recalculations on the LULUCF sector can be found in Table 9-5.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 9-2: Overall Impact of Recalculations by Sector Compared to Previous *Inventory*

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
Energy	16.8	1.6	(13.4)	(32.1)	(25.6)	(16.7)	(0.2)
IPPU	33.5	15.3	5.0	5.1	4.7	5.2	20.4
Agriculture	3.1	4.1	12.9	5.6	2.4	6.7	5.3
LULUCF	(95.8)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Waste	0.0	(0.1)	(0.5)	(0.2)	0.2	0.0	(0.1)
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 9-4 and Table 9-5 include the category-level quantitative effects of methodological changes and historical data updates made in the current *Inventory* in calculating CO_2-equivalent U.S. greenhouse gas emissions by gas across all sectors. To understand the details of any specific recalculation or methodological improvement, see the Recalculations sections within each source/sink categories' section found in Chapters 3 through 7 of this report. A discussion of *Inventory* improvements in response to review processes is described in Annex 8.

Key Recalculations and Improvements for 1990-2022 *Inventory*

The current *Inventory* includes new categories that improve completeness of the national estimates. Specifically, the current report includes CO_2 emissions from ceramics production and non-metallurgical magnesia production within other process use of carbonates category, fluorinated gases from fluorochemical production other than HCFC-22 within the fluorochemical production category, and managed forest land in Hawaii and several U.S. Territories.[1] The report also now includes SF_6 and PFCs from product uses.

The following source and sink categories underwent the most significant methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken are provided for these categories.

Table 9-3: Key Recalculations

Sector	Category	Reason for Recalculation or Improvement	Impact of Recalculation on 2021 Value	Average Impact over Time Series	
				Percent	(MMT CO_2 Eq.)
LULUCF	Forest Land Remaining Forest Land (CO_2)	Accuracy. Use of new and updated data and methods from the USFS Forest Inventory and Analysis program, see details in Chapter 6.2.	148.8	+21.7%	159.1
LULUCF	Land Converted to Grassland (CO_2)	Accuracy. Use of new activity data and methods from FIA, USDA-NRCS NRI and DayCent model, see details in Chapter 6.7.	49.2	-237.1%	53.1
LULUCF	Land Converted to Cropland (CO_2)	Accuracy. Use of new activity data and methods from FIA, USDA-NRCS NRI and DayCent model, see details in Chapter 6.5.	21.6	-36.6%	20.7

[1] American Samoa, Guam, Northern Marianas Islands, U.S. Virgin Islands, and Puerto Rico.

LULUCF	Grassland Remaining Grassland (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI, and re-calibration of the DayCent model, see details in Chapter 6.6.	0.6	+1,850.1%	10.7
Energy	Non-Energy Use of Fuels (CO_2)	Accuracy and Consistency. Use of new, updated, and recategorized data from U.S. International Trade Commission, EIA and other data sources (ACC), see details in Chapter 3.2.	28.6	-8.2%	10.1
LULUCF	Land Converted to Settlements (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI, FIA, and extended time series, see details in Chapter 6.11.	12.8	-9.3%	7.7
IPPU	Fluorochemical Production (HFCs)	Completeness. Inclusion of new subcategory fluorochemical production other than HCFC-22, see details in Chapter 4.14 and 4.15.	1.7	+58.7%	6.8
Energy	Fossil Fuel Combustion (CO_2)	Accuracy and Consistency. Use of updated data and alignment of methodology from EIA, see details in Chapter 3.1.	15.2	+0.1%	5.8
LULUCF	Cropland Remaining Cropland (CO_2)	Accuracy. Use of new data from USDA-NRCS NRI and the OpTIS remote-sensing data, and methods to extend time series, see details in Chapter 6.4.	13.0	+26.4%	4.2
Agriculture	Agricultural Soil Management (N_2O)	Accuracy. Use of updated time series data for land representation, re-calibration of DayCent model, and updated cropland management parameters, see details in Chapter 5.4.	3.9	+1.1%	3.3
Energy	Petroleum Systems (CH_4)	Accuracy. Use of additional data from GHGRP, see details in Chapter 3.6.	1.5	-4.6%	2.5
LULUCF	Wetlands Remaining Wetlands (CO_2)	Accuracy. Use of new data and updated emissions factors, see details in Chapter 1.8.	2.3	+2.2%	2.4

Figure 9-2: Impacts of Recalculations to U.S. Greenhouse Gas Emissions and Sinks by Sector

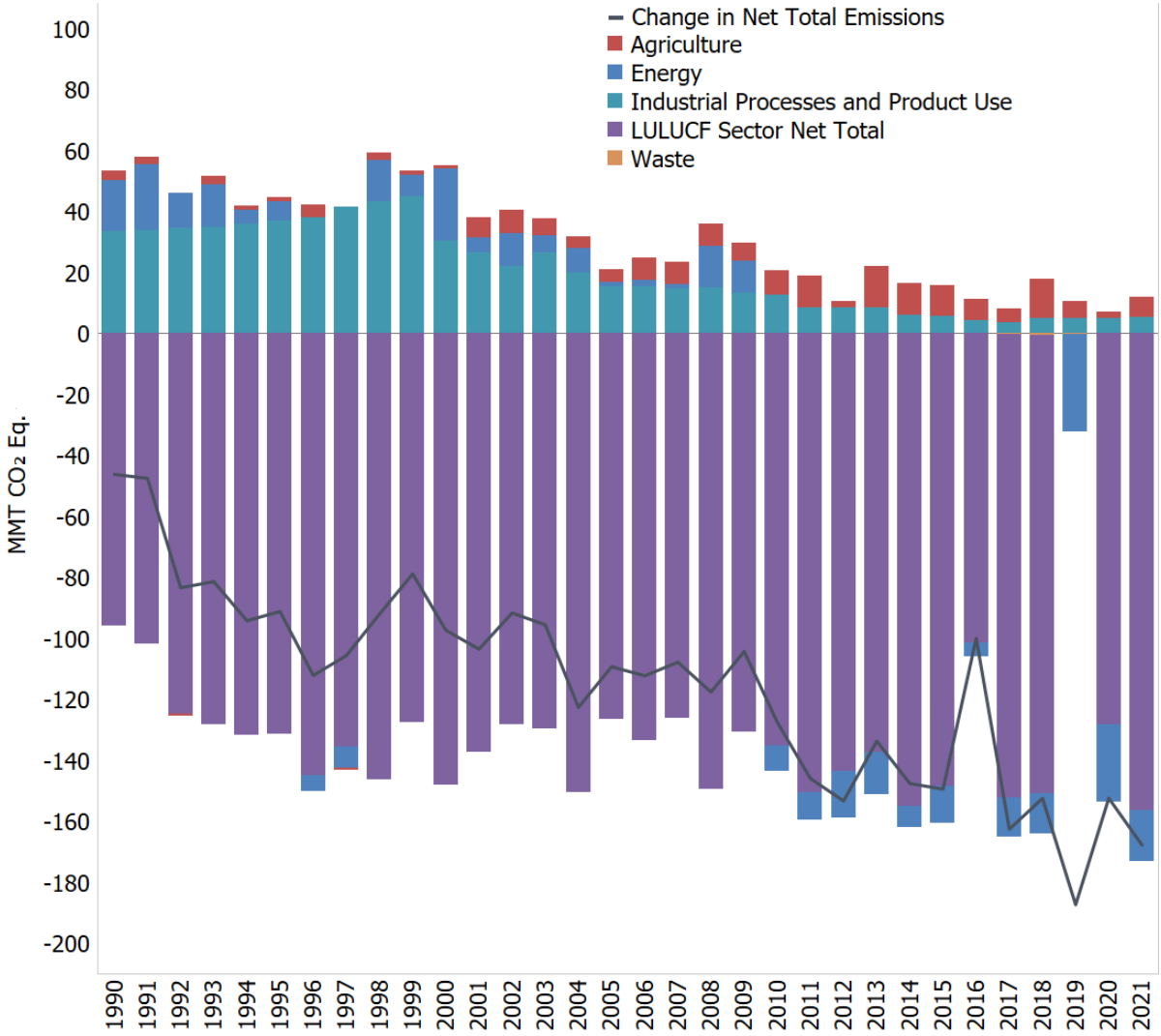


Table 9-4: Revisions to U.S. Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	Average Annual Change
CO_2	**10.7**	**(5.3)**	**(15.6)**	**(27.7)**	**(25.7)**	**(15.0)**	**(4.6)**
Fossil Fuel Combustion	*24.0*	*(3.2)*	*(1.7)*	*(3.3)*	*(3.2)*	*15.2*	*5.8*
Electric Power Sector	NC	NC	NC	NC	+	+	+
Transportation	NC	NC	0.2	0.2	0.3	1.1	0.1
Industrial	24.0	(3.2)	(3.1)	(6.1)	(5.9)	4.8	5.2
Residential	(+)	+	0.7	1.5	1.6	4.7	0.3
Commercial	(+)	+	0.5	1.0	0.8	4.5	0.2
U.S. Territories	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Non-Energy Use of Fuels	(13.3)	(3.9)	(11.1)	(21.1)	(21.5)	(28.6)	(10.1)
Natural Gas Systems	0.2	1.3	(+)	(+)	0.3	(0.4)	0.4
Cement Production	NC	NC	NC	NC	NC	NC	NC

Lime Production	NC	NC	NC	NC	NC	NC	NC
Other Process Uses of Carbonates[a]	0.9	1.0	0.6	0.6	0.6	0.6	0.8
Glass Production	0.3	(+)	NC	NC	NC	NC	+
Soda Ash Production	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Titanium Dioxide Production	NC	NC	NC	(0.1)	0.1	NC	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	0.2	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	NC	(+)	(+)
Urea Consumption for Non-Agricultural Purposes	NC	NC	+	(+)	(+)	1.6	0.1
Phosphoric Acid Production	NC	NC	NC	NC	NC	(+)	(+)
Petrochemical Production	(1.5)	(0.5)	(2.1)	(2.2)	(1.9)	(2.5)	(1.4)
Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Lead Production	NC	NC	NC	NC	(+)	(+)	(+)
Zinc Production	NC	NC	NC	NC	NC	+	+
Petroleum Systems	0.1	(+)	(1.3)	(1.4)	(0.1)	(0.5)	(0.1)
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	NC	NC	NC	(+)	+
Liming	NC	NC	NC	NC	(+)	(0.7)	(+)
Urea Fertilization	NC	NC	(+)	+	+	+	(+)
Coal Mining	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Substitution of Ozone Depleting Substances	NC	NC	NC	NC	NC	NC	NC
Biomass and Biodiesel Consumption[b]	*NC*	*NC*	*(+)*	*(+)*	*(9.9)*	*(12.3)*	*(0.7)*
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
CH_4[d]	**3.0**	**4.4**	**(2.6)**	**(13.4)**	**(6.9)**	**(7.0)**	**0.5**
Stationary Combustion	+	(+)	+	+	(0.8)	(0.9)	(+)
Mobile Combustion	+	(0.1)	(+)	(+)	(+)	(+)	(0.1)
Coal Mining	NC	(0.4)	NC	(+)	NC	(+)	(+)
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	(0.1)	(+)
Natural Gas Systems	3.7	6.9	(4.0)	(4.9)	(5.0)	(6.8)	1.9
Petroleum Systems	(1.9)	(2.7)	(1.6)	(7.7)	(1.2)	(1.5)	(2.5)
Abandoned Oil and Gas Wells	0.1	0.2	0.2	0.1	0.2	0.3	0.2
Petrochemical Production	(0.2)	(0.1)	(0.3)	(0.4)	(0.3)	(0.4)	(0.2)
Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	+	(+)	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	+	+	(+)	(+)	0.1	1.5	0.1
Manure Management	0.1	0.1	1.2	0.9	0.2	0.4	0.3
Rice Cultivation	1.0	0.4	2.5	(1.2)	1.0	1.5	1.0
Field Burning of Agricultural Residues	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Landfills	NC	(+)	(0.4)	(0.3)	(0.7)	(0.6)	(+)
Wastewater Treatment	(+)	(+)	(+)	(+)	(0.4)	(0.4)	(+)
Composting	NC	NC	NC	NC	NC	NC	NC
Anaerobic Digestion at Biogas Facilities	(+)	(+)	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[c]	NC	NC	NC	NC	NC	NC	NC
N_2O[d]	**1.9**	**3.4**	**9.3**	**6.1**	**2.3**	**4.9**	**3.9**
Stationary Combustion	0.1	(+)	(+)	(+)	(0.1)	(0.1)	+
Mobile Combustion	+	+	0.1	0.1	+	0.1	0.1
Adipic Acid Production	NC	NC	(+)	NC	NC	NC	(+)

Nitric Acid Production	NC	NC	NC	NC	NC	NC	NC
Manure Management	1.0	0.7	(0.6)	(0.6)	(0.6)	(0.3)	0.5
Agricultural Soil Management	0.8	2.6	9.7	6.3	1.6	3.9	3.3
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	NC	NC	+	0.3	1.4	1.1	0.1
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Caprolactam, Glyoxal, and Glyoxylic Acid Production	NC	NC	NC	NC	(+)	(+)	(+)
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	NC	NC
Electronics Industry	NC	NC	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
Petroleum Systems	(+)	(+)	+	(+)	(+)	(+)	(+)
International Bunker Fuels[c]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
HFCs, PFCs, SF_6 and NF_3	**34.0**	**14.8**	**6.8**	**7.2**	**6.1**	**5.7**	**21.2**
HFCs	**8.7**	**5.4**	**3.0**	**2.7**	**2.1**	**1.9**	**6.9**
Substitution of Ozone Depleting Substances	NC	0.1	0.1	0.1	0.1	0.2	0.1
Fluorochemical Production[e]	8.7	5.3	2.9	2.6	2.0	1.7	6.8
Electronics Industry	(+)	(+)	(+)	+	(+)	+	+
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
PFCs	**17.7**	**4.2**	**3.1**	**3.3**	**2.7**	**2.8**	**9.3**
Aluminum Production	NC	NC	NC	NC	NC	+	+
Fluorochemical Production	17.5*	4.0*	2.9*	3.0*	2.5*	2.6*	9.1*
Electronics Industry	(+)	+	0.1	0.1	0.1	+	+
Substitution of Ozone Depleting Substances	NC	+	(+)	(+)	(+)	(+)	(+)
SF_6 and PFCs from Other Product Use	0.1*	0.1*	0.2*	0.2*	0.2*	0.1*	0.1*
Electrical Equipment	+	(+)	NC	(+)	+	(+)	(+)
SF_6	**7.4**	**4.7**	**0.5**	**0.6**	**0.6**	**0.4**	**4.6**
Electrical Equipment	NC	+	(0.2)	(+)	+	+	(+)
SF_6 and PFCs from Other Product Use	1.3*	1.3*	0.8*	0.6*	0.5*	0.4*	1.2*
Fluorochemical Production	5.8*	3.3*	+	+	+	+	3.3*
Electronics Industry	NC	+	+	+	+	(+)	+
Magnesium Production and Processing	0.2	0.1	NC	NC	NC	+	0.1
NF_3	**0.3**	**0.6**	**0.1**	**0.6**	**0.7**	**0.5**	**0.5**
Electronics Industry	NC	NC	+	+	+	(+)	+
Fluorochemical Production	0.3*	0.6*	0.1*	0.6*	0.7*	0.5*	0.5*
Total Gross Emissions (Sources)	**49.6**	**17.3**	**(2.1)**	**(27.8)**	**(24.2)**	**(11.4)**	**21.0**
Percent Change in Total Emissions	**0.8%**	**0.2%**	**0.0%**	**-0.4%**	**-0.4%**	**(+)**	**0.3%**
Change in LULUCF Sector Net Total[f]	(95.8)	(126.5)	(150.4)	(159.5)	(128.2)	(156.3)	(135.8)
Net Emissions (Sources and Sinks)	**(46.2)**	**(109.3)**	**(152.4)**	**(187.3)**	**(152.4)**	**(167.8)**	**(114.8)**
Percent Change in Net Emissions	**-0.8%**	**-1.6%**	**-2.5%**	**-3.2%**	**-2.9%**	**-3.0%**	**-1.9%**

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

* Indicates a new source for the current *Inventory* year. Emissions from new sources are captured in net emissions and percent change totals.

[a] Category includes emissions from ceramics production (new subcategory, not estimated in the previous *Inventory*), other uses of soda ash, and non-metallurgical magnesia (new subcategory, not estimated in the previous *Inventory*) in the current *Inventory.*

[b] Emissions from biomass and biofuel consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[c] Emissions from international bunker fuels are not included in totals.

[d] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals in Table 9-4. LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland

fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands; and N_2O emissions from forest soils and settlement soils.

[e] This category was reported as HCFC-22 production in the 1990 to 2021 *Inventory*.

[f] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes. More detail on the impacts of recalculations on the LULUCF sector can be found in Table 9-5.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 9-5: Revisions to U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2017	2018	2019	2020	Average Annual Change
Forest Land Remaining Forest Land	**(153.1)**	**(164.6)**	**(170.4)**	**(169.0)**	**(162.4)**	**(153.4)**	**(160.7)**
Changes in Forest Carbon Stocks[a]	(153.3)	(161.8)	(169.1)	(163.8)	(154.6)	(148.8)	(159.1)
Non-CO_2 Emissions from Forest Fires[b]	0.3	(2.8)	(1.3)	(5.1)	(7.7)	(4.5)	(1.6)
N_2O Emissions from Forest Soils[c]	+	(+)	(+)	(+)	(+)	(+)	(+)
Non-CO_2 Emissions from Drained Organic Soils[d]	NC	NC	NC	NC	NC	NC	NC
Land Converted to Forest Land	**(1.8)**	**(1.7)**	**(2.1)**	**(2.0)**	**(2.0)**	**(2.1)**	**(1.8)**
Changes in Forest Carbon Stocks[e]	(1.8)	(1.7)	(2.1)	(2.0)	(2.0)	(2.1)	(1.8)
Cropland Remaining Cropland	**18.1**	**(2.6)**	**(1.2)**	**(4.9)**	**14.5**	**(13.0)**	**(4.2)**
Changes in Mineral and Organic Soil Carbon Stocks	18.1	(2.6)	(1.2)	(4.9)	14.5	(13.0)	(4.2)
Land Converted to Cropland	**(9.4)**	**(20.1)**	**(24.4)**	**(24.9)**	**(27.4)**	**(21.6)**	**(20.7)**
Changes in all Ecosystem Carbon Stocks[f]	(9.4)	(20.1)	(24.4)	(24.9)	(27.4)	(21.6)	(20.7)
Grassland Remaining Grassland	**15.7**	**13.2**	**17.8**	**14.2**	**10.5**	**0.9**	**10.8**
Changes in Mineral and Organic Soil Carbon Stocks	15.7	13.0	17.3	14.5	10.0	0.6	10.7
Non-CO_2 Emissions from Grassland Fires[g]	0.1	0.1	0.5	(0.3)	0.4	0.3	0.1
Land Converted to Grassland	**41.9**	**61.9**	**49.4**	**48.7**	**54.6**	**49.2**	**53.1**
Changes in all Ecosystem Carbon Stocks[f]	41.9	61.9	49.4	48.7	54.6	49.2	53.1
Wetlands Remaining Wetlands	**(4.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.7)**	**(3.9)**
Changes in Organic Soil Carbon Stocks in Peatlands	NC	NC	(0.1)	(0.1)	(0.1)	(0.2)	(+)
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(2.4)	(2.4)	(2.3)	(2.3)	(2.3)	(2.3)	(2.4)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Non-CO_2 Emissions from Peatlands Remaining Peatlands	NC	NC	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Flooded Land Remaining Flooded Land	(2.3)	(1.3)	(1.2)	(1.2)	(1.2)	(1.2)	(1.5)
Land Converted to Wetlands	**3.9**	**0.4**	**(0.1)**	**(0.1)**	**0.1**	**0.1**	**1.1**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Changes in Land Converted to Flooded Land	2.2	0.3	(+)	(+)	0.1	0.1	0.6
CH_4 Emissions from Land Converted to Flooded Land	1.8	0.2	(+)	(+)	+	+	0.5
Settlements Remaining Settlements	**(1.4)**	**(1.4)**	**(6.0)**	**(7.1)**	**(0.2)**	**0.2**	**(1.8)**
Changes in Organic Soil Carbon Stocks	(1.4)	(2.1)	(1.6)	(1.3)	(0.7)	(0.4)	(1.8)

Changes in Settlement Tree Carbon Stocks	(0.2)	0.4	(4.9)	(6.2)	0.1	+	(0.3)
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	NC	NC	NC	NC	NC	0.1	+
N_2O Emissions from Settlement Soils[h]	0.3	0.3	0.5	0.5	0.5	0.5	0.4
Land Converted to Settlements	**(5.2)**	**(7.9)**	**(9.7)**	**(10.9)**	**(12.2)**	**(12.8)**	**(7.7)**
Changes in all Ecosystem Carbon Stocks[f]	(5.2)	(7.9)	(9.7)	(10.9)	(12.2)	(12.8)	(7.7)
Change in LULUCF Total Net Flux[i]	**(95.8)**	**(123.0)**	**(148.8)**	**(153.4)**	**(120.2)**	**(151.4)**	**(133.6)**
Change in LULUCF Emissions[j]	**+**	**(3.6)**	**(1.6)**	**(6.2)**	**(8.0)**	**(4.9)**	**(2.2)**
CH_4	(0.4)	(2.8)	(1.8)	(4.4)	(6.1)	(3.8)	(2.0)
N_2O	0.4	(0.7)	0.2	(1.8)	(1.9)	(1.1)	(0.2)
Change in LULUCF Sector Net Total[k]	**(95.8)**	**(126.6)**	**(150.4)**	**(159.5)**	**(128.2)**	**(156.3)**	**(135.8)**
Percent Change in LULUCF Sector Net Total	**-10.9%**	**-16.2%**	**-19.7%**	**-22.7%**	**-16.5%**	**-20.7%**	**-17.0%**

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both forest land remaining forest land and land converted to forest land.

[c] Estimates include N_2O emissions from N fertilizer additions on both forest land remaining forest land and land converted to forest land.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both forest land remaining forest land and land converted to forest land. Carbon stock changes from drained organic soils are included with the forest land remaining forest land forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[h] Estimates include N_2O emissions from N fertilizer additions on both settlements remaining settlements and land converted to settlements because it is not possible to separate the activity data at this time.

[i] LULUCF carbon stock change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[k] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

10. References and Abbreviations

Executive Summary

BEA (2024) *2022 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2023/11).

IEA (2022) *Energy related CO_2 emissions, 2022,* International Energy Agency, Paris. Available online at: https://www.iea.org/reports/co2-emissions-in-2022.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K., Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

National Academies of Sciences, Engineering, and Medicine (2018) *Improving characterization of anthropogenic methane emissions in the United States*. Washington, DC: The National Academies Press. Available online at: https://doi.org/10.17226/24987.

National Research Council (2010) *Verifying greenhouse gas emissions: methods to support international climate agreements*. Washington, DC: The National Academies Press. Available online at: https://doi.org/10.17226/12883.

NOAA/ESRL (2024a) *Trends in Atmospheric Carbon Dioxide*. Available online at: https://gml.noaa.gov/ccgg/trends/. 05 January 2024.

NOAA/ESRL (2024b) *Trends in Atmospheric Methane.* Available online at: https://gml.noaa.gov/ccgg/trends_ch4/. 05 January 2024.

NOAA/ESRL (2024c) *Trends in Atmospheric Nitrous Oxide.* Available online at: https://gml.noaa.gov/ccgg/trends_n2o/. 05 January 2024.

UNFCCC (2014) *Report of the Conference of the Parties on its Nineteenth Session, Held in Warsaw from 11 to 23 November 2013*. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

U.S. Census Bureau (2024) U.S. Census Bureau International Database (IDB). Available online at: https://www.census.gov/programs-surveys/international-programs.html.

Introduction

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2014) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, J. Minx, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, and T. Zwickel (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1435 pp.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007*) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change.* [J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

IPCC/TEAP (2005) *Special Report: Safeguarding the Ozone Layer and the Global Climate System, Chapter 4: Refrigeration*. 2005. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/03/sroc04-1.pdf.

Meinhausen, M., et al. (2017) *Historical Greenhouse Gas Concentrations for Climate Modeling (CMIP6).* Available online at: https://gmd.copernicus.org/articles/10/2057/2017/.

NOAA (2017) Vital Signs of the Planet. Available online at: http://climate.nasa.gov/causes/. Accessed on 9 January 2017.

NOAA/ESRL (2024a) *Trends in Atmospheric Carbon Dioxide*. Available online at: https://gml.noaa.gov/ccgg/trends/gr.html. March 26, 2024.

NOAA/ESRL (2024b) *Trends in Atmospheric Methane.* Available online at: https://gml.noaa.gov/ccgg/trends_ch4/. March 26, 2024.

NOAA/ESRL (2024c) *Trends in Atmospheric Nitrous Oxide.* Available online at: https://gml.noaa.gov/ccgg/trends_n2o/. March 26, 2024.

NOAA/ESRL (2024d) *Trends in Atmospheric Sulfur Hexafluoride*. Available online at: https://gml.noaa.gov/ccgg/trends_sf6/. March 26, 2024.

Rigby, M., et al. (2010) *History of Atmospheric SF_6 from 1973 to 2008.* Available online at: www.atmos-chem-phys.net/10/10305/2010. March 23, 2024.

UNEP/WMO (1999) Information Unit on Climate Change. Framework Convention on Climate Change. Available online at: http://unfccc.int.

UNFCCC (2014) *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013*. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

USGCRP (2017) *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp, doi: 10.7930/J0J964J6. Available online at: https://science2017.globalchange.gov/.

WMO/UNEP (2018) Scientific Assessment of Ozone Depletion: 2018. Available online at: https://csl.noaa.gov/assessments/ozone/2018.

Trends in Greenhouse Gas Emissions

BEA (2024) 2022 *Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2023/11).

EIA (2020) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: http://www.eia.gov/petroleum/fueloilkerosene.

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 – 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) *2023 EPA Automotive Trends Report.* Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/automotive-trends/download-automotive-trends-report.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K., Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Census Bureau (2024) U.S. Census Bureau International Database (IDB). Available online at: https://www.census.gov/programs-surveys/international-programs.html.

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA/NASS) (2023) Farm Production Expenditures Annual Summary. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington DC. Available online at: https://usda.library.cornell.edu/concern/publications/qz20ss48r?locale=en.

Energy

EIA (2024) *Monthly Energy Review, February 2024*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2024/02).

IEA (2022) *Energy related CO_2 emissions, 2022*, International Energy Agency, Paris. Available online at: https://www.iea.org/reports/co2-emissions-in-2022.

Carbon Dioxide Emissions from Fossil Fuel Combustion

AAR (2008 through 2022) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Private communication with Dan Keen.

AISI (2004 through 2021) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

APTA (2007 through 2020) *Public Transportation Fact Book.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/resources/statistics/Pages/transitstats.aspx.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, D.C.

BEA (2024) *2022 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2022*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: http://www.bea.gov/national/index.htm#gdp.

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Benson, D. (2002 through 2004) Unpublished data. Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning (2022a) Addressing the Time Series Inconsistency in FHWA Data. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2022.

Browning (2022b) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2022.

Browning, L. (2020) *GHG Inventory EF Development Using Certification Data.* Technical Memo, September 2020.

Browning, L. (2019) Updated On-highway CH_4 and N_2O Emission Factors for GHG Inventory. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2019.

Browning, L. (2018a) Updated Methodology for Estimating Electricity Use from Highway Plug-In Electric Vehicles. Technical Memo, October 2018.

Browning, L. (2018b) Updated Non-Highway CH_4 and N_2O Emission Factors for U.S. GHG Inventory. Technical Memo, November 2018.

Browning, L. (2017) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Technical Memo, October 2017.

Coffeyville Resources Nitrogen Fertilizers (2012) Nitrogen Fertilizer Operations. Available online at: http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html.

Dakota Gasification Company (2006) *CO_2 Pipeline Route and Designation Information*. Bismarck, ND.

DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.

DLA Energy (2022) Unpublished data from the Fuels Automated System (FAS). Defense Logistics Agency Energy, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1991 through 2020) *Transportation Energy Data Book*. *Edition 40*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978. Personal Communication between Stacy Davis (DOE) and Deep Shah (ICF) for sharing selected tables from the pre-release version.

DOE (2012) *2010 Worldwide Gasification Database*. National Energy Technology Laboratory and Gasification Technologies Council. Available online at: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html. Accessed on 15 March 2012.

DOT (1991 through 2023) *Airline Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: http://www.transtats.bts.gov/fuel.asp.

Eastman Gasification Services Company (2011) Project Data on Eastman Chemical Company's Chemicals-from-Coal Complex in Kingsport, TN.

EIA (2024a) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035 (2024/02).

EIA (2024b) International Energy Statistics 1980-2022. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/beta/international/.

EIA (2024c) *Quarterly Coal Report: January – September 2023*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0121.

EIA (2023a) *Natural Gas Annual 2022.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(20).

EIA (2023b). *Petroleum Supply Annual 2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/petroleum/.

EIA (2023c) Form EIA-923 detailed data with previous form data (EIA-906/920), Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA. November 2023.

EIA (2023d) *Annual Coal Report 2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0584.

EIA (2022) "Energy use in homes." *Use of energy explained.* Available online at: https://www.eia.gov/energyexplained/use-of-energy/homes.php.

EIA (2020a) Glossary. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: https://www.eia.gov/tools/glossary/?id=electricity.

EIA (2020b) "Natural gas prices, production, consumption, and exports increased in 2019." *Today in Energy*. Available online at: https://www.eia.gov/todayinenergy/detail.php?id=37892.

EIA (2018) "Both natural gas supply and demand have increased from year-ago levels." Today in Energy. Available online at: https://www.eia.gov/todayinenergy/detail.php?id=37193.

EIA (2009a) *Emissions of Greenhouse Gases in the United States 2008, Draft Report.* Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE-EIA-0573 (2009).

EIA (2009b) *Manufacturing Consumption of Energy (MECS) 2006*. U.S. Department of Energy, Energy Information Administration, Washington, D.C. Released July 2009.

EIA (2008) *Historical Natural Gas Annual, 1930 – 2008*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/renewable/.

EIA (2001) *U.S. Coal, Domestic and International Issues*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. March 2001.

EIA (1990-2001) *State Energy Data System*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

Environment and Climate Change Canada (2022) Personal Communication between Environment and Climate Change Canada and Vincent Camobreco for imported CO_2. March 2022.

EPA (2024) Acid Rain Program Dataset 1996-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2023) The 2023 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/automotive-trends.

EPA (2022) *Motor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/moves.

EPA (2021) The Emissions & Generation Resource Integrated Database (eGRID) 2019 Technical Support Document. Clean Air Markets Division, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available Online at: https://www.epa.gov/sites/default/files/2021-02/documents/egrid2019_technical_guide.pdf

EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Erickson, T. (2003) *Plains CO_2 Reduction (PCOR) Partnership*. Presented at the Regional Carbon Sequestration Partnership Meeting Pittsburgh, Pennsylvania, Energy and Environmental Research Center, University of North Dakota. November 3, 2003.

FAA (2024) Personal Communication between FAA and John Steller, Mausami Desai, and Vincent Camobreco for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). March 2024.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm.

FHWA (2015) *Off-Highway and Public-Use Gasoline Consumption Estimation Models Used in the Federal Highway Administration*, Publication Number FHWA-PL-17-012. Available online at: https://www.fhwa.dot.gov/policyinformation/pubs/pl17012.pdf.

Fitzpatrick, E. (2002) *The Weyburn Project: A Model for International Collaboration*.

FRB (2022) *Industrial Production and Capacity Utilization*. Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at: http://www.federalreserve.gov/releases/G17/table1_2.htm.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.Marland, G. and A. Pippin (1990) "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity." *Energy Systems and Policy,* 14(4):323.

NREL (2023) "NREL Researchers Reveal How Buildings Across United States Do—and Could—Use Energy." Available online at: https://www.nrel.gov/news/features/2023/nrel-researchers-reveal-how-buildings-across-the-united-

states-do-and-could-use-energy.html#:~:text=Buildings%20are%20responsible%20for%2040,building%20stock%20is%20also%20essential.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

U.S. Aluminum Association (USAA) (2008 through 2021) U*.S. Primary Aluminum Production*. U.S. Aluminum Association, Washington, D.C.

USAF (1998) Fuel Logistics Planning. U.S. Air Force: AFPAM23-221. May 1, 1998.

U.S. Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary*. Available online at: https://www.census.gov/data/tables/time-series/econ/cir/mq325b.html.

United States Geological Survey (USGS) (2020a) *2020 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2021b) *2021 Mineral Commodity Summary: Titanium and Titanium Dioxide*. U.S. Geological Survey, Reston, VA.

USGS (2019) *2017 Mineral Yearbook: Aluminum.* U.S. Geological Survey, Reston, VA

USGS (2014 through 2021a) *Mineral Industry Surveys: Silicon*. U.S. Geological Survey, Reston, VA.

USGS (2014 through 2021b) *Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA.

USGS (2014 through 2019) *Minerals Yearbook: Nitrogen [Advance Release*]. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/.

USGS (1991 through 2020) *Minerals Yearbook – Iron and Steel Scrap*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2015a) *Minerals Yearbook: Manufactured Abrasives Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/abrasives/.

USGS (1991 through 2015b) *Minerals Yearbook: Titanium*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2015c) *Minerals Yearbook: Silicon Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/silicon/.

USGS (1996 through 2013) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

USGS (1995 through 2013) *Minerals Yearbook: Lead Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995, 1998, 2000, 2001, 2002, 2007) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Stationary Combustion (excluding CO_2)

EIA (2024a) *Monthly Energy Review, February 2024*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2024b) *International Energy Statistics 1980-2022*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/international/data/world.

EPA (2024) Acid Rain Program Dataset 1996-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2022) *MOtor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/moves.

EPA (1997) Compilation of Air Pollutant Emission Factors, AP-42. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

Mobile Combustion (excluding CO_2)

AAR (2008 through 2023) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Private communication with Dan Keen.

ANL (2022) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET2022)*. Argonne National Laboratory. October 2022. Available online at: https://greet.es.anl.gov.

APTA (2007 through 2023) *Public Transportation Fact Book.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/resources/statistics/Pages/transitstats.aspx.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, D.C. Available online at: http://www.apta.com/research/stats/rail/crsum.cfm.

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Benson, D. (2002 through 2004) Personal communication. Unpublished data developed by the Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Browning (2022a) Addressing the Time Series Inconsistency in FHWA Data. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2022.

Browning (2022b) Updated Methodology for Estimating CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2022.

Browning (2020) *GHG Inventory EF Development Using Certification Data*. Memorandum from ICF to Sarah Roberts, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2020.

Browning, L. (2019) Updated On-highway CH_4 and N_2O Emission Factors for GHG Inventory. Memorandum from ICF to Sarah Roberts and Justine Geidosch, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. September 2019.

Browning, L. (2018) Updated Non-Highway CH_4 and N_2O Emission Factors for U.S. GHG Inventory. Technical Memorandum from ICF International to Sarah Roberts and Justine Geidosch, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2018.

Browning, L. (2005) Personal communication with Lou Browning, "Emission control technologies for diesel highway vehicles specialist," ICF International.

BTS (2023) *Amtrak Fuel Consumption and Travel.* Bureau of Transportation Statistics, Washington, DC. Available online at: https://www.bts.gov/content/amtrak-fuel-consumption-and-travel-1.

DLA Energy (2022) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1993 through 2022) *Transportation Energy Data Book Edition 40*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. Personal Communication between Stacy Davis (DOE) and Deep Shah (ICF) for sharing selected tables from the pre-release version.

DOT (1991 through 2023) Airline *Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: http://www.transtats.bts.gov/fuel.asp.

EIA (2024) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2023) *Natural Gas Annual 2022*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0131(22).

EIA (1991 through 2022) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: http://www.eia.gov/petroleum/fueloilkerosene.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: http://www.eia.doe.gov/fuelrenewable.html.

EPA (2023) Annual Certification Test Results Report. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-test-data-vehicles-and-engines.

EPA (2022a) *Motor Vehicle Emissions Simulator (MOVES3)*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/moves.

EPA (2022b) Confidential Engine Family Sales Data Submitted to EPA by Manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

EPA (2004) *Mobile6.2 Vehicle Emission Modeling Software*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

EPA (1999) *Emission Facts: The History of Reducing Tailpipe Emissions.* Office of Mobile Sources. May 1999. EPA 420-F-99-017. Available online at: https://www.epa.gov/nscep.

EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–1996*. Office of Mobile Sources, Assessment and Modeling Division, U.S. Environmental Protection Agency. August 1998. EPA420-R-98-009.

EPA (1994a) *Automobile Emissions: An Overview.* Office of Mobile Sources. August 1994. EPA 400-F-92-007. Available online at: https://www.epa.gov/nscep.

EPA (1994b) *Milestones in Auto Emissions Control.* Office of Mobile Sources. August 1994. EPA 400-F-92-014. Available online at: https://www.epa.gov/nscep.

Esser, C. (2003 through 2004) Personal Communication with Charles Esser, Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.

FAA (2022) Personal Communication between FAA and John Steller, Mausami Desai and Vincent Camobreco for aviation emission estimates from the Aviation Environmental Design Tool (AEDT). March 2022.

FHWA (1996 through 2023) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual.

FTA (2023) National Transit Database "Fuel and Energy by Mode and TOS" table. Available online at: https://data.transportation.gov/.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2006) 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

ICF (2006) *Revised Gasoline Vehicle EFs for LEV and Tier 2 Emission Levels.* Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2004) *Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles*. Final Report to U.S. Environmental Protection Agency. February 2004.

RailInc (2014 through 2023) *RailInc Short line and Regional Traffic Index.* Carloads Originated Year-to-Date. November 2023. Available online at: https://public.railinc.com/.

Whorton, D. (2006 through 2014) Personal communication, Class II and III Rail energy consumption, American Short Line and Regional Railroad Association.

Carbon Emitted from Non-Energy Uses of Fossil Fuels

ACC (2023a) "U.S. Resin Production & Sales 2022 vs. 2021." Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry/resources/pips-resin-sales-and-production-cy-figures-2022-vs-2021.

ACC (2023b) *Guide to the Business of Chemistry, 2023*, American Chemistry Council. Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2023-guide-to-the-business-of-chemistry.

ACC (2022) "U.S. Resin Production & Sales 2021 vs. 2020." Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry.

ACC (2021) "U.S. Resin Production & Sales 2020 vs. 2019." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2020) "U.S. Resin Production & Sales 2019 vs. 2018." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2019) "U.S. Resin Production & Sales 2018 vs. 2017." Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2018) “U.S. Resin Production & Sales 2017 vs. 2016.” Available online at: https://www.americanchemistry.com/chemistry-in-america/chemistry-in-everyday-products/plastics.

ACC (2017) “U.S. Resin Production & Sales 2016 vs. 2015.”

ACC (2016) “U.S. Resin Production & Sales 2015 vs. 2014.”

ACC (2015) “PIPS Year-End Resin Statistics for 2014 vs. 2013: Production, Sales and Captive Use.” Available online at: https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/statistics-on-the-plastic-resins-industry/resin-report-subscriptions.

ACC (2014) "U.S. Resin Production & Sales: 2013 vs. 2012,” American Chemistry Council. Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

ACC (2013) “U.S. Resin Production & Sales: 2012 vs. 2011,” American Chemistry Council. Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

ACC (2003-2011) “PIPS Year-End Resin Statistics for 2010: Production, Sales and Captive Use.” Available online at: http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf.

Bank of Canada (2023) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2022) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2021) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2020) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2019) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/#download.

Bank of Canada (2018) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/annual-average-exchange-rates/.

Bank of Canada (2017) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2016) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2014) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2013) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

Bank of Canada (2012) Financial Markets Department Year Average of Exchange Rates. Available online at: https://www.bankofcanada.ca/rates/exchange/legacy-noon-and-closing-rates/.

CIAC (2022). 2022 Economic Review of Chemistry. Available online at: https://canadianchemistry.ca/wp-content/uploads/2022/06/2022-Economic-Review-of-Chemistry23732_removed.pdf.

EIA (2024) *Monthly Energy Review, February 2024.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035 (2024/02). Available online at: https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

EIA (2021) *EIA Manufacturing Consumption of Energy (MECS) 2018.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2020) Glossary. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: https://www.eia.gov/tools/glossary/index.php?id=N#nat_Gas_Liquids.

EIA (2019) Personal communication between EIA and ICF on November 11, 2019.

EIA (2017) *EIA Manufacturing Consumption of Energy (MECS) 2014.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2013) *EIA Manufacturing Consumption of Energy (MECS) 2010.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2010) *EIA Manufacturing Consumption of Energy (MECS) 2006.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2005) *EIA Manufacturing Consumption of Energy (MECS) 2002.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2001) *EIA Manufacturing Consumption of Energy (MECS) 1998.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1997) *EIA Manufacturing Consumption of Energy (MECS) 1994.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1994) *EIA Manufacturing Consumption of Energy (MECS) 1991.* U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EPA (2023) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C.

EPA (2021) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2019) *Advancing Sustainable Materials Management: 2016 and 2017 Data Tables*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf.

EPA (2018a) Advancing Sustainable Materials Management: Facts and Figures 2015, Assessing Trends in Material Generation, Recycling and Disposal in the United States. Washington, D.C.

EPA (2018b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2017) EPA's Pesticides Industry Sales and Usage, 2008 – 2012 Market Estimates. Available online at: https://www.epa.gov/sites/production/files/2017-01/documents/pesticides-industry-sales-usage-2016_0.pdf. Accessed September 2017.

EPA (2016a) Advancing Sustainable Materials Management: 2014 Facts and Figures Fact Sheet. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.

EPA (2016b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2015) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2014a) Municipal Solid Waste in the United States: 2012 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/default/files/2015-09/documents/2012_msw_dat_tbls.pdf.

EPA (2014b) Chemical Data Access Tool (CDAT). U.S. Environmental Protection Agency, June 2014. Available online at: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B2D73C764-6919-404D-8C9B-61869B3330D6%7D. Accessed January 2015.

EPA (2013a) Municipal Solid Waste in the United States: 2011 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm.

EPA (2013b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2011) EPA's Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates. Available online at: https://www.epa.gov/pesticides/pesticides-industry-sales-and-usage-2006-and-2007-market-estimates. Accessed January 2012.

EPA (2009) Biennial Reporting System (BRS) Database. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: https://www.epa.gov/enviro/br-search. Data for 2001-2007 are current as of Sept. 9, 2009.

EPA (2004) EPA's Pesticides Industry Sales and Usage, 2000 and 2001 Market Estimates. Available online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=3000659P.TXT. Accessed September 2006.

EPA (2002) EPA's Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates, Table 3.6. Available online at https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200001G5.TXT. Accessed July 2003.

EPA (2001) AP 42, Volume I, Fifth Edition. Chapter 11: Mineral Products Industry. Available online at: http://www.epa.gov/ttn/chief/ap42/ch11/index.html.

EPA (2000a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: https://www.epa.gov/enviro/br-search.

EPA (2000b) *Toxics Release Inventory, 1998*. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, D.C. Available online at: https://enviro.epa.gov/triexplorer/tri_release.chemical.

EPA (1999) EPA's Pesticides Industry Sales and Usage, 1996-1997 Market Estimates. Available online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200001IL.TXT.

EPA (1998) EPA's Pesticides Industry Sales and Usage, 1994-1995 Market Estimates. Available online at: http://www.epa.gov/oppbead1/pestsales/95pestsales/market_estimates1995.pdf.

FEB (2013) Fiber Economics Bureau, as cited in C&EN (2013) Lackluster Year for Chemical Output: Production stayed flat or dipped in most world regions in 2012. Chemical &Engineering News, American Chemical Society, 1 July. Available online at: http://www.cen-online.org.

FEB (2012) Fiber Economics Bureau, as cited in C&EN (2012) Too Quiet After the Storm: After a rebound in 2010, chemical production hardly grew in 2011. Chemical & Engineering News, American Chemical Society, 2 July. Available online at: http://www.cen-online.org.

FEB (2011) Fiber Economics Bureau, as cited in C&EN (2011) *Output Ramps up in all Regions*. Chemical Engineering News, American Chemical Society, 4 July. Available online at: http://www.cen-online.org.

FEB (2010) Fiber Economics Bureau, as cited in C&EN (2010) *Output Declines in U.S., Europe*. Chemical & Engineering News, American Chemical Society, 6 July. Available online at: http://www.cen-online.org.

FEB (2009) Fiber Economics Bureau, as cited in C&EN (2009) *Chemical Output Slipped In Most Regions* Chemical & Engineering News, American Chemical Society, 6 July. Available online at: http://www.cen-online.org.

FEB (2007) Fiber Economics Bureau, as cited in C&EN (2007) *Gains in Chemical Output Continue*. Chemical & Engineering News, American Chemical Society. July 2, 2007. Available online at: http://www.cen-online.org.

FEB (2005) Fiber Economics Bureau, as cited in C&EN (2005) *Production: Growth in Most Regions* Chemical & Engineering News, American Chemical Society, 11 July. Available online at: http://www.cen-online.org.

FEB (2003) Fiber Economics Bureau, as cited in C&EN (2003) *Production Inches Up in Most Countries,* Chemical & Engineering News, American Chemical Society, 7 July. Available online at: http://www.cen-online.org.

FEB (2001) Fiber Economics Bureau, as cited in ACS (2001) *Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole* Chemical & Engineering News, American Chemical Society, 25 June. Available online at: http://pubs.acs.org/cen.

Financial Planning Association (2006) Canada/US Cross-Border Tools: US/Canada Exchange Rates. Available online at: http://www.fpanet.org/global/planners/US_Canada_ex_rates.cfm. Accessed on August 16, 2006.

Gosselin, Smith, and Hodge (1984) "Clinical Toxicology of Commercial Products." Fifth Edition, Williams & Wilkins, Baltimore.

ICIS (2016) “Production issues force US melamine plant down” Available online at: https://www.icis.com/resources/news/2016/05/03/9994556/production-issues-force-us-melamine-plant-down/.

ICIS (2008) “Chemical profile: Melamine” Available online at: https://www.icis.com/resources/news/2008/12/01/9174886/chemical-profile-melamine/. Accessed November 2017.

IISRP (2003) “*IISRP Forecasts Moderate Growth in North America to 2007*” International Institute of Synthetic Rubber Producers, Inc. New Release. Available online at: http://www.iisrp.com/press-releases/2003-Press-Releases/IISRP-NA-Forecast-03-07.html.

IISRP (2000) "Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA" International Institute of Synthetic Rubber Producers press release.

INEGI (2006) Producción bruta total de las unidades económicas manufactureras por Subsector, Rama, Subrama y Clase de actividad. Available online at: http://www.inegi.gob.mx/est/contenidos/espanol/proyectos/censos/ce2004/tb_manufacturas.asp. Accessed on August 15, 2006.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Marland, G., and R.M. Rotty (1984) “Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982,” Tellus 36b:232-261.

NPRA (2002) North American Wax - A Report Card. Available online at: http://www.npra.org/members/publications/papers/lubes/LW-02-126.pdf.

U.S. Census Bureau (2021) 2017 Economic Census. Available online at: https://www.census.gov/data/tables/2017/econ/economic-census/naics-sector-31-33.html. Accessed October 2021.

U.S. Census Bureau (2014) 2012 Economic Census. Available online at: http://www.census.gov/econ/census/schedule/whats_been_released.html. Accessed November 2014.

U.S. Census Bureau (2009) *Soap and Other Detergent Manufacturing: 2007*.

U.S. Census Bureau (2004) *Soap and Other Detergent Manufacturing: 2002*. Issued December 2004. EC02-31I-325611 (RV). Available online at: http://www.census.gov/prod/ec02/ec0231i325611.pdf.

U.S. Census Bureau (1999) *Soap and Other Detergent Manufacturing: 1997*. Available online at: http://www.census.gov/epcd/www/ec97stat.htm.

U.S. International Trade Commission (2023) "Interactive Tariff and Trade DataWeb: Quick Query." Available online at: http://dataweb.usitc.gov/. Accessed September 2023.

USTMA (2022) "2021 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2022. Available online at: https://www.ustires.org/sites/default/files/21%20US%20Scrap%20Tire%20Management%20Report%20101722.pdf.

USTMA (2020) "2019 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2020. Available online at: https://www.ustires.org/sites/default/files/2019%20USTMA%20Scrap%20Tire%20Management%20Summary%20Report.pdf.

USTMA (2018) "2017 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. July 2018. Available online at: https://www.tyrepress.com/wp-content/uploads/2018/07/USTMA_scraptire_summ_2017_07_11_2018.pdf.

USTMA (2016) "2015 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. August 2016. Available online at: https://www.ustires.org/sites/default/files/MAR_028_USTMA.pdf.

USTMA (2014) "2013 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. November 2014. Available online at: https://www.ustires.org/sites/default/files/MAR_027_USTMA.pdf.

USTMA (2013) "U.S. Scrap Tire Management Summary 2005-2009." U.S. Tire Manufacturers Association. October 2011; Updated September 2013. Available online at: https://www.ustires.org/sites/default/files/MAR_025_USTMA.pdf.

USTMA (2012) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." U.S. Tire Manufacturers Association. Accessed 18 on January 2012.

Incineration of Waste

ArSova, Ljupka, Rob van Haaren, Nora Goldstein, Scott M. Kaufman, and Nickolas J. Themelis (2008) "16th Annual BioCycle Nationwide Survey: The State of Garbage in America" *BioCycle*, JG Press, Emmaus, PA. December.

Bahor, B (2009) Covanta Energy's public review comments re: *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007.* Submitted via email on April 9, 2009 to Leif Hockstad, U.S. EPA.

De Soete, G.G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control." In A. R. Van Amstel, (ed.) Proc. of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort, NL. February 3-5, 1993.

Energy Recovery Council (2018) Energy Recovery Council. *2018 Directory of Waste to Energy Facilities*. Ted Michaels and Karunya Krishnan. October 2018. Available online at: http://energyrecoverycouncil.org/wp-content/uploads/2019/10/ERC-2018-directory.pdf.

Energy Recovery Council (2009) "2007 Directory of Waste-to-Energy Plants in the United States." Accessed on September 29, 2009.

EIA (2019) EIA St. Louis Federal Reserve's Economic Data (FRED) Consumer Price Index for All Urban Consumers: Education and Communication (CPIEDUSL). Available online at: https://www.eia.gov/opendata/excel/.

EIA (2017) *MSW Incineration for Heating or Electrical Generation, December 2017,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035. Available online at: https://www.eia.gov/opendata/?src=-f3.

EPA (2022) Greenhouse Gas Reporting Program (GHGRP). 2022 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2020a) Advancing Sustainable Materials Management: 2018 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2020-11/documents/2018_ff_fact_sheet.pdf.

EPA (2020b) Greenhouse Gas Reporting Program (GHGRP). 2020 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2019) Advancing Sustainable Materials Management: 2016 and 2017 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2019-11/documents/2016_and_2017_facts_and_figures_data_tables_0.pdf.

EPA (2018a) Advancing Sustainable Materials Management: 2015 Data Tables. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2018b) Greenhouse Gas Reporting Program Data. Washington, DC: U.S. Environmental Protection Agency. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

EPA (2016) *Advancing Sustainable Materials Management: 2014 Fact Sheet*. Office of Land and Emergency Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.

EPA (2015) *Advancing Sustainable Materials Management: Facts and Figures 2013 – Assessing Trends in Material Generation, Recycling and Disposal in the United States.* Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www3.epa.gov/epawaste/nonhaz/municipal/pubs/2013_advncng_smm_rpt.pdf.

EPA (2007, 2008, 2011, 2013, 2014) *Municipal Solid Waste in the United States: Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www.epa.gov/osw/nonhaz/municipal/msw99.html.

EPA (2006) *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C.

EPA (2000) *Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update.* Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. EPA530-F-00-024.

Goldstein, N. and C. Madtes (2001) "13th Annual BioCycle Nationwide Survey: The State of Garbage in America." *BioCycle*, JG Press, Emmaus, PA. December 2001.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kaufman, et al. (2004) "14th Annual BioCycle Nationwide Survey: The State of Garbage in America 2004" Biocycle, JG Press, Emmaus, PA. January 2004.

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States–A National Survey. Thesis. Columbia University, Department of Earth and Environmental Engineering, January 3, 2014.

Simmons, et al. (2006) "15th Nationwide Survey of Municipal Solid Waste Management in the United States: The State of Garbage in America." BioCycle, JG Press, Emmaus, PA. April 2006.

USTMA (2022) "2021 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2022. Available online at: https://www.ustires.org/sites/default/files/21%20US%20Scrap%20Tire%20Management%20Report%20101722.pdf.

USTMA (2020) "2019 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. October 2020. Available online at: https://www.ustires.org/sites/default/files/2019%20USTMA%20Scrap%20Tire%20Management%20Summary%20Report.pdf.

USTMA (2018) "2017 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association, Washington, DC. July 2018. Available online at: https://www.tyrepress.com/wp-content/uploads/2018/07/USTMA_scraptire_summ_2017_07_11_2018.pdf.

USTMA (2016) "2015 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. August 2016. Available online at: https://www.ustires.org/sites/default/files/MAR_028_USTMA.pdf.

USTMA (2014) "2013 U.S. Scrap Tire Management Summary." U.S. Tire Manufacturers Association. November 2014. Available online at: https://www.ustires.org/sites/default/files/MAR_027_USTMA.pdf.

USTMA (2013) "U.S. Scrap Tire Management Summary 2005-2009." U.S. Tire Manufacturers Association. October 2011; Updated September 2013. Available online at: https://www.ustires.org/sites/default/files/MAR_025_USTMA.pdf.

USTMA (2012a) "Rubber FAQs." U.S. Tire Manufacturers Association. Accessed on 19 November 2014.

USTMA (2012b) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." U.S. Tire Manufacturers Association. Accessed 18 on January 2012.

van Haaren, Rob, Themelis, N., and Goldstein, N. (2010) "The State of Garbage in America." BioCycle, October 2010. Volume 51, Number 10, pg. 16-23.

Coal Mining

AAPG (1984) *Coalbed Methane Resources of the United States.* AAPG Studies in Geology Series #17.

Creedy, D.P. (1993) Methane Emissions from Coal Related Sources in Britain: Development of a Methodology. *Chemosphere,* 26: 419-439.

DMME (2023) *DGO Data Information System*. Department of Mines, Minerals and Energy of Virginia. Available online at https://www.dmme.virginia.gov/dgoinquiry/frmmain.aspx.

EIA (2023) *Annual Coal Report 2022*. Table 1. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0584.

El Paso (2009) Shoal Creek Mine Plan, El Paso Exploration & Production.

EPA (2023) Greenhouse Gas Reporting Program (GHGRP) 2022 Subpart FF: Underground Coal Mines.

EPA (2005) *Surface Mines Emissions Assessment.* Draft. U.S. Environmental Protection Agency.

EPA (1996) *Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States*. EPA/600/R-96-065. U.S. Environmental Protection Agency.

ERG (2023). Correspondence between ERG and Buchanan Mine.

Geological Survey of Alabama State Oil and Gas Board (GSA) (2023) Well Records Database. Available online at http://www.gsa.state.al.us/ogb/database.aspx.

IEA (2022) *Coal 2022*, International Energy Agency, Paris, License: CC BY 4.0. Available online at: https://www.iea.org/reports/coal-2022.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories*. Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia. Eds: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M. IGES.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

JWR (2010) *No. 4 & 7 Mines General Area Maps.* Walter Energy: Jim Walter Resources.

King, Brian (1994) *Management of Methane Emissions from Coal Mines: Environmental, Engineering, Economic and Institutional Implication of Options.* Neil and Gunter Ltd.

McElroy OVS (2023) Marshall County VAM Abatement Project Offset Verification Statement submitted to California Air Resources Board, August 2023.

MSHA (2023) Data Transparency at MSHA. Mine Safety and Health Administration. Available online at http://www.msha.gov/.

Mutmansky, Jan M. and Yanbei Wang (2000) Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions. *Mineral Resources Engineering,* 9(4).

Saghafi, Abouna (2013) *Estimation of Fugitive Emissions from Open Cut Coal Mining and Measurable Gas Content.* 13th Coal Operators' Conference, University of Wollongong, The Australian Institute of Mining and Metallurgy & Mine Managers Association of Australia. 306-313.

USBM (1986) *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*. Circular 9067. U.S. Bureau of Mines.

West Virginia Geological & Economic Survey (WVGES) (2023) Oil & Gas Production Data. Available online at http://www.wvgs.wvnet.edu/www/datastat/datastat.htm.

Abandoned Underground Coal Mines

CMOP (2023) EPA's Coalbed Methane Outreach Program, Map of US Coal Mine Methane Current Projects and Potential Opportunities. Available online at: https://www.epa.gov/cmop/map-us-coal-mine-methane-current-projects-and-potential-opportunities.

COGIS (2018) Colorado Oil and Gas Information System. Colorado Oil and Gas Commission, Department of Natural Resources. Available online at https://cogcc.state.co.us/data.html.

EPA (2004) Methane Emissions Estimates & Methodology for Abandoned Coal Mines in the U.S. Draft Final Report. Washington, D.C. April 2004.

GMI (2021) Global Methane Initiative, International Coal Mine Methane Database. Available online at: https://www.globalmethane.org/resources/details.aspx?resourceid=1981.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

MSHA (2023) U.S. Department of Labor, Mine Health & Safety Administration, Mine Data Retrieval System. Available online at: https://www.msha.gov/mine-data-retrieval-system..

Petroleum Systems

API (1992) *Global Emissions of Methane from Petroleum Sources*. American Petroleum Institute, Health and Environmental Affairs Department, Report No. DR140, February 1992.

BOEM (2023a) BOEM Platform Structures Online Query. Available online at: https://www.data.boem.gov/Platform/PlatformStructures/Default.aspx.

BOEM (2023b) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1947 to 2022. Download "Production Data" online at: https://www.data.boem.gov/Main/RawData.aspx.

BOEM (2023c) BOEM Oil and Gas Operations Reports - Part A (OGOR-A). Production Data for 1996 to 2022. Available online at: https://www.data.boem.gov/Main/OGOR-A.aspx.

BOEM (2023d) BOEM Oil and Gas Operations Reports - Part B (OGOR-B). Flaring volumes for 1996 to 2022. Available online at: https://www.data.boem.gov/Main/OGOR-B.aspx.

EIA (2023) Crude Oil Production. Energy Information Administration.

Enverus (2023) September 2023 Download. Enverus, Inc.

EPA (2023) *Greenhouse Gas Reporting Program*. U.S. Environmental Protection Agency. Data reported as of August 18, 2023.

EPA (2017) *2017 Nonpoint Oil and Gas Emission Estimation Tool*, Version 1.2. Prepared for U.S. Environmental Protection Agency by Eastern Research Group, Inc. (ERG). October 2019.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report).* Prepared by ICF International. Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

EPA/GRI (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Natural Gas Systems

AHS (2022) U.S. Census Bureau's *American Housing Survey* (AHS). https://www.census.gov/programs-surveys/ahs.html.

CBECS (2023) Energy Information Administration's Commercial Buildings Energy Consumption Survey (CBECS). https://www.eia.gov/consumption/commercial.

CenSARA (2012) *2011 Oil and Gas Emission Inventory Enhancement Project for CenSARA States*. Prepared by ENVIRON International Corporation and Eastern Research Group, Inc. (ERG). Central States Air Resources Agencies (CenSARA). December 2012.

Cusworth, D.H., Duren, R.M., Thorpe, A.K., Pandey S., Maasakkers, J.D., Aben, I., et al. (2021). *Multisatellite imaging of a gas well blowout enables quantification of total methane emissions.* Geophysical Research Letters, 48, e2020GL090864. https://doi.org/10.1029/2020GL090864.

EIA (2023a) Natural Gas Gross Withdrawals and Production. Energy Information Administration.

EIA (2023b) October 2021 *Monthly Energy Review*. Energy Information Administration. https://www.eia.gov/totalenergy/data/monthly/archive/00352110.pdf.

Enverus (2023) September 2023 Download. Enverus, Inc.

EPA (2023a) MOVES3. https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

EPA (2023b) *Greenhouse Gas Reporting Program- Subpart W – Petroleum and Natural Gas Systems*. Environmental Protection Agency. Data reported as of August 18, 2023.

EPA (2022) Nonpoint Oil & Gas Emission estimation Tool.

EPA (1977) *Atmospheric Emissions from Offshore Oil and Gas Development and Production*. Office of Air Quality Planning and Standards, Research Triangle Park, NC. PB272268. June 1977.

Evans, D.J. & Chadwick, R.A. (2009) (eds) "Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe." *The Geological Society,* London, Special Publications, 313: 173–216. https://doi.org/10.1144/SP313.12.

FERC (2023) Form No. 2, Major Natural Gas Pipeline Annual Report. Federal Energy Regulatory Commission. https://ferc.gov/industries-data/natural-gas/industry-forms.

Fischer et al. (2018) "An Estimate of Natural Gas Methane Emissions from California Homes." *Environmental Science & Technology* 2018, *52 (17)*, 10205–10213. https://pubs.acs.org/doi/10.1021/acs.est.8b03217.

GRI/EPA (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

GTI (2019) *Classification of Methane Emissions from Industrial Meters, Vintage vs Modern Plastic Pipe, and Plastic-lined Steel and Cast-Iron Pipe*. June 2019. Gas Technology Institute and U.S. Department of Energy GTI Project Number 22070. DOE project Number ED-FE0029061.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

Illinois Office of Oil and Gas Resource Management (2022) State-level natural gas production quantities.

Indiana Division of Oil & Gas (2022) State-level natural gas production quantities.

Kansas Department of Health and Environment (2022) County-level produced water quantities.

Lamb, et al. (2015) "Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States." *Environmental Science & Technology, Vol. 49* 5161-5169.

Lavoie et al. (2017) "Assessing the Methane Emissions from Natural Gas-Fired Power Plants and Oil Refineries." *Environmental Science & Technology*. 2017 Mar 21;51(6):3373-3381. doi: 10.1021/acs.est.6b05531.

Li, H Z et al. (2022) "A national estimate of U.S. underground natural gas storage incident emissions." *Environmental Research Letters*. 17: 084013. https://doi.org/10.1088/1748-9326/ac8069.

Maasakkers, Joannes D., Mark Omara, Ritesh Gautam, Alba Lorente, Sudhanshu Pandey, Paul Tol, Tobias Borsdorff, Sander Houweling, Ilse Aben (2022). *Reconstructing and quantifying methane emissions from the full duration of a 38-day natural gas well blowout using space-based observations.* Remote Sensing of Environment. https://doi.org/10.1016/j.rse.2021.112755.

Ohio Environmental Protection Agency (2022) Well-level produced water quantities.

Oklahoma Department of Environmental Quality (2022) Well-level produced water quantities.

Pandey, S., Gautam, R., Houweling, S., van der Gon, H. D., Sadavarte, P., Borsdorff, T., et al. (2019). *Satellite observations reveal extreme methane leakage from a natural gas well blowout*. Proceedings of the National Academy of Sciences, 116, 26376– 26381. https://doi.org/10.1073/pnas.1908712116.

PHMSA (2022a) Gas Distribution Annual Data. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at: https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-gas-distribution-systems.

PHMSA (2022b) Underground Natural Gas STAR, Part C. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids.

West Virginia Department of Environmental Protection (2020) State-level natural gas production quantities.

Zimmerle et al. (2019) "Characterization of Methane Emissions from Gathering Compressor Stations." October 2019. Available at https://mountainscholar.org/handle/10217/195489.

Zimmerle et al. (2015) "Methane Emissions from the Natural Gas Transmission and Storage System in the United States." *Environmental Science and Technology, Vol. 49* 9374–9383.

Abandoned Oil and Gas Wells

Alaska Oil and Gas Conservation Commission, Available online at: https://www.commerce.alaska.gov/web/aogcc/Data.aspx.

Arkansas Geological & Conservation Commission, "List of Oil & Gas Wells - Data From November 1, 1936 to January 1, 1955."

The Derrick's Handbook of Petroleum: A Complete Chronological and Statistical Review of Petroleum Developments From 1859 to 1898 (V.1), (1898-1899) (V.2).

Enverus (2023) October 2023 Download. Enverus, Inc.

Florida Department of Environmental Protection - Oil and Gas Program, Available online at: https://floridadep.gov/water/oil-gas.

Geological Survey of Alabama, Oil & Gas Board, Available online at: https://www.gsa.state.al.us/ogb/.

GRI/EPA (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

Interstate Oil and Gas Compact Commission (2021). IDLE AND ORPHAN OIL AND GAS WELLS: STATE AND PROVINCIAL REGULATORY STRATEGIES 2021. Available online at: https://iogcc.ok.gov/sites/g/files/gmc836/f/iogcc_idle_and_orphan_wells_2021_final_web.pdf.

Kang, et al. (2016) "Identification and characterization of high methane-emitting abandoned oil and gas wells." *PNAS*, vol. 113 no. 48, 13636–13641, doi: 10.1073/pnas.1605913113.

Oklahoma Geological Survey. "Oklahoma Oil: Past, Present, and Future." Oklahoma Geology Notes, v. 62 no. 3, 2002 pp. 97-106.

Pennsylvania Department of Environmental Protection, Oil and Gas Reports - Oil and Gas Operator Well Inventory. Available online at: http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Well_Inventory.

International Bunker Fuels

Anderson, B.E., et al. (2011) *Alternative Aviation Fuel Experiment (AAFEX)*, NASA Technical Memorandum, in press.

ASTM (1989) *Military Specification for Turbine Fuels, Aviation, Kerosene Types*, NATO F-34 (JP-8) and NATO F-35. February 10, 1989.

DHS (2008) Personal Communication with Elissa Kay, Residual and Distillate Fuel Oil Consumption (International Bunker Fuels). Department of Homeland Security, Bunker Report. January 11, 2008.

DLA Energy (2023) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2022) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOT (1991 through 2013) Fuel Cost and Consumption. Federal Aviation Administration, Bureau of Transportation.

Statistics, U.S. Department of Transportation. Washington, D.C. DAI-10.

EIA (2024) *Monthly Energy Review, February 2024,* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2024/02).

EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

FAA (2024) Personal Communication between FAA and John Steller, Mausami Desai, and Vincent Camobreco for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). March 2024.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.USAF (1998) Fuel Logistics Planning. U.S. Air Force pamphlet AFPAM23-221, May 1, 1998.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. 31 Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic 32 Co-Operation and Development, International Energy Agency, Paris, France.

Wood Biomass and Biofuel Consumption

EIA (2024a) *Monthly Energy Review, February 2024*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2024/02).

EIA (2024b) Biofuels explained: Use of biomass-based diesel fuel. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: https://www.eia.gov/energyexplained/biofuels/use-of-biodiesel.php.

EPA (2023). Greenhouse Gas Reporting Program (GHGRP). 2022 Envirofacts. Available online at: https://ghgdata.epa.gov/ghgp/main.do.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Lindstrom, P. (2006) Personal Communication. Perry Lindstrom, Energy Information Administration and Jean Kim, ICF International.

Energy Sources of Precursor Greenhouse Gases

EPA (2023a) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C.

EPA (2023b) "Criteria pollutants National Tier 1 for 1970 – 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023c) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Industrial Processes and Product Use

EPA (2014) *Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014*. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

EPA (2002) Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis, U.S. Greenhouse

Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories* (Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia) eds.: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M., Pub. IGES, Japan 2011.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

Cement Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Bureau of Mines (1990 through 1993) *Minerals Yearbook: Cement Annual Report.* U.S. Department of the Interior, Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart H -National Level Clinker Production from Cement Production for Calendar Years 2014 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) *2021 Minerals Yearbook – Cement (Advance Release Tables)*. U.S. Geological Survey, Reston, VA. July 2023.

USGS (2023b) *Mineral Commodity Summaries: Cement*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023c) *Mineral Industry Surveys, Cement in December 2022*. U.S. Geological Survey, Reston, VA. (March 2023).

USGS (1995 through 2014) *Minerals Yearbook - Cement*. U.S. Geological Survey, Reston, VA.

Van Oss (2013a) 1990 through 2012 Clinker Production Data Provided by Hendrik van Oss (USGS) via email on November 8, 2013.

Van Oss (2013b) Personal communication. Hendrik van Oss, Commodity Specialist of the U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. October 28, 2013.

Lime Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Males, E. (2003) Memorandum from Eric Males, National Lime Association to William N. Irving & Leif Hockstad, Environmental Protection Agency. March 6, 2003.

Miner, R. and B. Upton (2002) Methods for estimating greenhouse gas emissions from lime kilns at kraft pulp mills. Energy. Vol. 27 (2002), p. 729-738.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Seeger (2013) Memorandum from Arline M. Seeger, National Lime Association to Leif Hockstad, Environmental Protection Agency. March 15, 2013.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart S-National Lime Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) (1996 through 2023) *Mineral Commodities Summary: Lime*. U.S. Geological Survey, Reston, VA (January 2023). Latest edition was updated in 2023 for 2022. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information.

USGS (2023b) (*2002 through 2021) Minerals Yearbook Annual Tables: Lime*. U.S. Geological Survey, Reston, VA (January 2023). Latest edition was updated in 2023 for 2021 tables. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information.

USGS (2021) *(1991 through 2018) Minerals Yearbook: Lime*. U.S. Geological Survey, Reston, VA (October 2021). Latest edition was updated in 2021 for 2018. Applicable editions are available at: https://www.usgs.gov/centers/national-minerals-information-center/lime-statistics-and-information. See "Archive" for editions prior to 1993.

USGS (2012) *2012* Expert Elicitation. Michael Miller, U.S. Geological Survey (2012).

Glass Production

Federal Reserve (2023) Board of Governors of the Federal Reserve System (US), Industrial Production: Manufacturing: Durable Goods: Glass and Glass Product (NAICS = 3272) [IPG3272N], retrieved from FRED, Federal Reserve Bank of St. Louis. Available at: https://fred.stlouisfed.org/series/IPG3272N. Accessed on November 21, 2023.

IPCC (2006) *2006 IPCC Guidelines* for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

RTI (2022) Expert judgment. Melissa Icenhour, RTI International. November 16, 2022.

U.S. Bureau of Mines (1991 and 1993a) Minerals Yearbook: Crushed Stone Annual Report. U.S. Department of the Interior. Washington, D.C.

U.S. Department of Energy (DOE) (2002) Glass Industry of the Future: Energy and Environmental Profile of the U.S. Glass Industry. Office of Industrial Technologies, U.S. Department of Energy. Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart N -National Glass Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2009) Technical Support Document for the Glass Manufacturing Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases. U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (1995 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2023) *Mineral Industry Surveys: Soda Ash in January 2023*. U.S. Geological Survey, Reston, VA. November 2023. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/soda-ash-statistics-and-information.

USGS (2022) *Mineral Industry Surveys: Soda Ash in June 2022*. U.S. Geological Survey, Reston, VA. November 2022. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2021) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2020) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2019) *Mineral Industry Surveys: Soda Ash in December 2018*. U.S. Geological Survey, Reston, VA. March 2019. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2018) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. 2018. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

USGS (2017) *Minerals Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017. Available online at: Index of /minerals-information-archives/soda_ash (usgs.gov).

Other Process Uses of Carbonates

AISI (2018 through 2021) *Annual Statistical Report.* American Iron and Steel Institute.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kostick, D. S. (2012) Personal communication. Dennis S. Kostick, U.S. Geological Survey, Soda Ash Commodity Specialist and Gopi Manne and Bryan Lange of Eastern Research Group, Inc. October 2012.

McNeece (2023) Personal communication, Steve McNeece, Nevada Department of Environmental Quality and Amanda Chiu, U.S. Environmental Protection Agency. November 28, 2023.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Simmons (2024) Personal communication, Kristi Simmons, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency. February 9, 2024.

U.S. Bureau of Mines (1991 and 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, D.C.

U.S. Environmental Protection Agency (EPA) (2023). Greenhouse Gas Reporting Program (GHGRP). Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/

United States Geological Survey (USGS) (2023a) *Mineral Industry Surveys: Soda Ash in September 2023*. U.S. Geological Survey, Reston, VA. November 2023.

USGS (2023b) *2021 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2023.

USGS (2022a) *Mineral Industry Surveys: Soda Ash in August 2022*. U.S. Geological Survey, Reston, VA. November 2022.

USGS (2022b) *2020 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2022c) *2018 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2022d) *2019 Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2022.

USGS (2022e) *2018 Minerals Yearbook: Magnesium Compounds [Advanced Release]*. U.S. Geological Survey, Reston, VA. May 2022.

USGS (2022f) *2018 Minerals Yearbook: Clay and Shale [Advanced Release]*. U.S. Geological Survey, Reston, VA. March 2022.

USGS (2022g) *2018 Minerals Yearbook: Soda Ash [Advanced Release]*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021a) *Minerals Yearbook 2019: Soda Ash [Advanced Data Release of the 2019 Annual Tables]*. U.S. Geological Survey, Reston, VA. August 2021.

USGS (2021b) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2021c) 2017 *Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. June 2021.

USGS (2021d) *2020 Mineral Commodity Summaries: Stone (Crushed).* U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020a) *Minerals Yearbook 2017: Stone, Crushed [Advanced Data Release of the 2017 Annual Tables]*. U.S. Geological Survey, Reston, VA. August 2020.

USGS (2020b) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020.

USGS (2020c) 2016 *Minerals Yearbook: Stone, Crushed [Advanced Release]*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2019) *Mineral Industry Surveys: Soda Ash in April 2019*. U.S. Geological Survey, Reston, VA. July 2019.

USGS (2018) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. 2018.

USGS (2017) *Mineral Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017.

USGS (1995a through 2017) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1994 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1990 through 2002) *Minerals Yearbook: Magnesium Compounds Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1948) *Reports: Magnesite and brucite deposits at Gabbs, Nye County, Nevada*. U.S. Geological Survey, Reston, VA

Willett (2023) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency. November 21, 2023.

Willett (2017) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Mausami Desai and John Steller, U.S. Environmental Protection Agency. March 9, 2017.

Ammonia Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Coffeyville Resources Energy, Inc. (CVR) (2008) *CVR Energy, Inc. 2008 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2022) CVR Energy, Inc. *2022 Annual Report on Form 10-K.* Available online at: https://cvrenergy.gcs-web.com/annual-report-proxy-information.

CVR (2021) CVR Energy, Inc. *2021 CVI Annual Report on Form 10-K.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2020) CVR Energy, Inc. *2020 CVI Annual Report on Form 10-K --Final*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2019) CVR Energy, Inc. *2019 CVI Form 10-K - Final*. Available online at https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2018) CVR Energy, Inc. *2018 CVI Annual Report on Form 10-K --Final*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2017) CVR Energy, Inc. *2017 CVI Annual Report on Form 10-K (Web).* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2016) CVR Energy, Inc. *2016 CVI Annual Report on Form 10-K (Web).* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2014) CVR Energy, Inc. *2014 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2015) CVR Energy, Inc. *2015 Annual Report*. Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2013) CVR Energy, Inc. *2013 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2012) *CVR Energy, Inc. 2012 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2011) *CVR Energy, Inc. 2011 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2010) *CVR Energy, Inc. 2010 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

CVR (2009) *CVR Energy, Inc. 2009 Annual Report.* Available online at: https://cvrenergy.gcs-web.com/annual-report-and-proxy-archive.

EFMA (2000) *Best Available Techniques for Pollution Prevention* and *Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate. Available online at: http://fertilizerseurope.com/site/index.php?id=390.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2010) *Current Industrial Reports Fertilizer Materials and Related Products: 2009 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2009) *Current Industrial Reports Fertilizer Materials and Related Products: 2008 Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2008) *Current Industrial Reports Fertilizer Materials and Related Products: 2007 Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b/mq325b075.xls.

U.S. Census Bureau (2007) *Current Industrial Reports Fertilizer Materials and Related Products: 2006 Summary*. Available online at: http://www.census.gov/industry/1/mq325b065.pdf.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer Materials and Related Products: 2005 Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (2004, 2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (1998 through 2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports Summary*. Available online at: http://www.census.gov/cir/www/325/mq325b.html.

U.S. Census Bureau (1991 through 1994) *Current Industrial Reports Fertilizer Materials Annual Report.* Report No. MQ28B. U.S. Census Bureau, Washington, D.C.

United States EIA (2023) *Monthly Energy Review, February 2023,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2023/2).

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G -Annual Urea Production from Ammonia Manufacturing for Calendar Years 2017-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G - Annual Urea Production from Ammonia Manufacturing for Calendar Years 2011-2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C

United States Geological Survey (USGS) (2023) *2023 Mineral Commodity Summaries: Nitrogen (Fixed) - Ammonia.* January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nitrogen.pdf.

USGS (1994-2009) *Minerals Yearbook: Nitrogen*. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/

Urea Consumption for Non-Agricultural Purposes

EFMA (2000) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

TFI (2002) *U.S. Nitrogen Imports/Exports Table.* The Fertilizer Institute. Available online at: http://www.tfi.org/statistics/usnexim.asp. August 2002.

United States Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary.* Available online at: http://www.census.gov/manufacturing/cir/historical_data/index.html.

United States Department of Agriculture (2012) Economic Research Service Data Sets, Data Sets, U.S. Fertilizer Imports/Exports: Standard Tables. Available online at: http://www.ers.usda.gov/data-products/fertilizer-importsexports/standard-tables.aspx.

U.S. EPA (2023a) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G -Annual Urea Production from Ammonia Manufacturing for Calendar Years 2017-2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2023b). Greenhouse Gas Reporting Program. Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart G - Annual Urea Production from Ammonia Manufacturing for Calendar Years 2011-2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States International Trade Commission (ITC) (2002) *United States International Trade Commission Interactive Tariff and Trade DataWeb, Version 2.5.0*. Available online at: http://dataweb.usitc.gov/. August 2002.

United States Geological Survey (USGS) (1994 through 2023a) *Minerals Yearbook: Nitrogen*. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/.

USGS (2023b) *Minerals Commodity Summaries: Nitrogen (Fixed) – Ammonia*. January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nitrogen.pdf.

Nitric Acid Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Icenhour (2020) Personal communication, Melissa Icenhour, RTI International and Amanda Chiu, U.S. Environmental Protection Agency. December 3, 2020.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (2010a) *Current Industrial Reports. Fertilizers and Related Chemicals: 2009.* "Table 1: Summary of Production of Principle Fertilizers and Related Chemicals: 2009 and 2008." June, 2010. MQ325B(08)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2010b) Personal communication between Hilda Ward (of U.S. Census Bureau) and Caroline Cochran (of ICF International). October 26, 2010 and November 5, 2010.

U.S. Census Bureau (2009) *Current Industrial Reports. Fertilizers and Related Chemicals: 2008.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2004 to 2008." June, 2009. MQ325B(08)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Census Bureau (2008) *Current Industrial Reports. Fertilizers and Related Chemicals: 2007.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2003 to 2007." June, 2008. MQ325B(07)-5. Available online at: http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. EPA (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart V - National Nitric Acid Production for Calendar Years 2017 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2018) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart V - National Nitric Acid Production for Calendar Years 2010 through 2016. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2010) *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Nitric Acid Production Industry.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. December 2010. Available online at: http://www.epa.gov/nsr/ghgdocs/nitricacid.pdf.

U.S. EPA (1998) *Compilation of Air Pollutant Emission Factors, AP-42.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. February 1998.

Adipic Acid Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Ard (2024) Personal communication, Howard Ard, Florida Department of Environmental Protection and Amanda Chiu, U.S. Environmental Protection Agency. February 6, 2024.

Ascend (2023) "Ascend reaches GHG abatement milestone." Available online at https://www.ascendmaterials.com/news/ascend-reaches-ghg-abatement-milestone. December 1, 2023.

C&EN (1995) "Production of Top 50 Chemicals Increased Substantially in 1994." *Chemical & Engineering News*, 73(15):17. April 10, 1995.

C&EN (1994) "Top 50 Chemicals Production Rose Modestly Last Year." *Chemical & Engineering News*, 72(15):13. April 11, 1994.

C&EN (1993) "Top 50 Chemicals Production Recovered Last Year." *Chemical & Engineering News*, 71(15):11. April 12, 1993.

C&EN (1992) "Production of Top 50 Chemicals Stagnates in 1991." *Chemical & Engineering News*, 70(15): 17. April 13, 1992.

CMR (2001) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. July 16, 2001.

CMR (1998) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. June 15, 1998.

CW (2005) "Product Focus: Adipic Acid." *Chemical Week*. May 4, 2005.

CW (1999) "Product Focus: Adipic Acid/Adiponitrile." *Chemical Week*, p. 31. March 10, 1999.

Desai (2010, 2011) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Adipic Acid Plant Engineers. 2010 and 2011.

ICIS (2007) "Adipic Acid." *ICIS Chemical Business Americas*. July 9, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A. and Triner, V.G. (1999) "Implementation of Technologies for Abatement of N_2O Emissions Associated with Adipic Acid Manufacture." Proceedings of the 2nd Symposium on Non-CO_2 Greenhouse Gases (NCGG-2), Noordwijkerhout, The Netherlands, 8-10 Sept. 1999, Ed. J. van Ham et al., Kluwer Academic Publishers, Dordrecht, pp. 347-358.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Thiemens, M.H., and W.C. Trogler (1991) "Nylon production; an unknown source of atmospheric nitrous oxide." *Science* 251:932-934.

United States Environmental Protection Agency (EPA) (2021 through 2023) Greenhouse Gas Reporting Program. Subpart E Data. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2019, 2020) Greenhouse Gas Reporting Program. Subpart E, S-CEMS, BB, CC, LL Data Set (XLSX) (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2014 through 2018) Greenhouse Gas Reporting Program. Subpart E, S-CEMS, BB, CC, LL Data Set (XLSX) (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Available online at: http://www2.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

U.S. EPA (2010 through 2013) Analysis of Greenhouse Gas Reporting Program data – Subpart E (Adipic Acid), Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Caprolactam, Glyoxal and Glyoxylic Acid Production

American Chemistry Council (ACC) (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

AdvanSix (2023) AdvanSix's Hopewell Facility Fact Sheet. Retrieved from: https://www.advansix.com/hopewell/about-us/ on September 13, 2023.

BASF (2023) Welcome to BASF in Freeport Texas. Retrieved from https://www.basf.com/us/en/who-we-are/organization/locations/featured-sites/Freeport.html on September 13, 2023.

ChemView (2021). Compilation of data submitted under TSCA in 2012 and 2016. Accessed April 2021. Available at https://chemview.epa.gov/chemview.

Cline, D. (2019) Firm to Clean Up and Market Former Fibrant Site. *The Augusta Chronicle*. September 9, 2019. Retrieved from https://www.augustachronicle.com.

Ecofys, et al. (2009). *Methodology for the free allocation of emission allowances in the EU ETS post 2012: Sector Report for the Chemical Industry*. Prepared by Ecofys, Fraunhofer Institute for Systems and Innovation Research, and Oko-Institut for the European Commission. November 2009. Available at https://ec.europa.eu/clima/system/files/2016-11/bm_study-chemicals_en.pdf.

ICIS (2006) Chemical Profile – Caprolactam. October 15, 2006. Available online at: https://www.icis.com/explore/resources/news/2006/10/18/2016832/chemical-profile-caprolactam/.

ICIS (2004) Chemical Profile – Caprolactam. January 5, 2004. Available online at: https://www.icis.com/explore/resources/news/2005/12/02/547244/chemical-profile-caprolactam/.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Shaw Industries Group, Inc. (Shaw) (2015) "Shaw Carpet Recycling Facility Successfully Processes Nylon and Polyester". July 13, 2015. Available online at: https://shawinc.com/Newsroom/Press-Releases/Shaw-Carpet-Recycling-Facility-Successfully-Proces/.

Textile World (2000) "Evergreen Makes Nylon Live Forever". Textile World. October 1, 2000. Available online at: https://www.textileworld.com/textile-world/textile-news/2000/10/evergreen-makes-nylon-live-forever/.

Carbide Production and Consumption

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Biscay, Nicolas & Henry, Lucile & Adschiri, Tadafumi & Yoshimura, Masahiro & Aymonier, Cyril. (2021). Behavior of Silicon Carbide Materials under Dry to Hydrothermal Conditions. Nanomaterials. 11. 1351. doi: 10.3390/nano11051351.

Environment and Climate Change Canada (ECCC) (2022), Personal Communication between Genevieve Leblanc-Power, Environment and Climate Change Canada and Mausami Desai and Amanda Chiu, U.S. Environmental Protection Agency. April 12, 2022.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Census Bureau (1990 through 2022) *USITC Trade DataWeb.* Available online at: http://dataweb.usitc.gov/.

USGS (1991a through 2021) *Minerals Yearbook: Manufactured Abrasives Annual Report.* U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/manufactured-abrasives-statistics-and-information.

USGS (1991b through 2021) *Minerals Yearbook: Silicon Annual Report.* U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/silicon/.

USGS (2023a) 2022 *Minerals Yearbook: Manufactured Abrasives (2022 advanced-release tables),* September 27, 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/manufactured-abrasives-statistics-and-information

USGS (2023b) *Mineral Commodity Summaries: Abrasives (Manufactured)*. U.S. Geological Survey, Reston, Va. January 2023.

USGS (2023c) *2022 Minerals Yearbook: Silicon (2022 advanced-release tables*), November 27, 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/silicon-statistics-and-information

USGS (2021a) *Mineral Commodity Summaries: Abrasives (Manufactured)*. U.S. Geological Survey, Reston, Va. January 2021. Available online at: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-abrasives.pdf.

Washington Mills (2023), North Grafton, MA. Available online at: https://www.washingtonmills.com/silicon-carbide/sic-industries. Accessed on April 4, 2023.

Titanium Dioxide Production

Gambogi, J. (2002) Telephone communication. Joseph Gambogi, Commodity Specialist, U.S. Geological Survey and Philip Groth, ICF International. November 2002.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) 2020 *Minerals Yearbook: Titanium*, 2020 tables-only release, Table 1. U.S. Geological Survey, Reston, Va. March 2023.

USGS (2023b) *Mineral Commodity Summaries: Titanium and Titanium Dioxide*. U.S. Geological Survey, Reston, Va. January 2023.

USGS (1991 through 2022) *Minerals Yearbook: Titanium.* U.S. Geological Survey, Reston, VA.

Soda Ash Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) *Mineral Commodity Summary: Soda Ash*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *Mineral Industry Surveys: Soda Ash in June 2023*. U.S. Geological Survey, Reston, VA. August 2023.

United States Geological Survey (USGS) (2022a) *Mineral Commodity Summary: Soda Ash*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2022b) *Mineral Industry Surveys: Soda Ash in June 2022*. U.S. Geological Survey, Reston, VA. August 2022.

USGS (2021) *Mineral Industry Surveys: Soda Ash in April 2021*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2020) *Mineral Industry Surveys: Soda Ash in April 2020*. U.S. Geological Survey, Reston, VA. July 2020.

USGS (2019) *Mineral Industry Surveys: Soda Ash in April 2019*. U.S. Geological Survey, Reston, VA. July 2019.

USGS (2018a) *Mineral Industry Surveys: Soda Ash in February 2018*. U.S. Geological Survey, Reston, VA. Accessed September 2018.

USGS (2017) *Mineral Industry Surveys: Soda Ash in January 2017*. U.S. Geological Survey, Reston, VA. March 2017.

USGS (2016) *Mineral Industry Surveys: Soda Ash in November 2016*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2015a) *Mineral Industry Surveys: Soda Ash in July 2015*. U.S. Geological Survey, Reston, VA. September 2015.

USGS (1994 through 2015b, 2018b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995c) *Trona Resources in the Green River Basin, Southwest Wyoming.* U.S. Department of the Interior, U.S. Geological Survey. Open-File Report 95-476. Wiig, Stephen, Grundy, W.D., Dyni, John R.

Petrochemical Production

ACC (2023) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

AN (2014) *About Acrylonitrile: Production*. AN Group, Washington, D.C.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, G. L. (2005 through 2010) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caroline Cochran, ICF International. September 2010.

Johnson, G. L. (2003) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caren Mintz, ICF International. November 2003.

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Aggregation of Reported Facility Level Data under Subpart X -National Petrochemical Production for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (2008) *Technical Support Document for the Petrochemical Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases.* U.S. Environmental Protection Agency. September 2008.

U.S. EPA (2000) *Economic Impact Analysis for the Proposed Carbon Black Manufacturing NESHAP,* U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA-452/D-00-003. May 2000.

HCFC-22 Production

ARAP (2010) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 10, 2010.

ARAP (2009) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 21, 2009.

ARAP (2008) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 17, 2008.

ARAP (2007) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 2, 2007.

ARAP (2006) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. July 11, 2006.

ARAP (2005) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 9, 2005.

ARAP (2004) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. June 3, 2004.

ARAP (2003) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 18, 2003.

ARAP (2002) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 7, 2002.

ARAP (2001) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 6, 2001.

ARAP (2000) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 13, 2000.

ARAP (1999) Facsimile from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger Schaefer of the U.S. Environmental Protection Agency. September 23, 1999.

ARAP (1997) Letter from Dave Stirpe, Director, Alliance for Responsible Atmospheric Policy to Elizabeth Dutrow of the U.S. Environmental Protection Agency. December 23, 1997.

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

RTI (2008) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22:Emissions from 1990 through 2006." Report prepared by RTI International for the Climate Change Division. March 2008.

RTI (1997) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22: Emissions from 1990 through 1996." Report prepared by Research Triangle Institute for the Cadmus Group. November 25, 1997; revised February 16, 1998.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Production of Fluorochemicals Other Than HCFC-22

3M (2024) *3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions.* February 2024.

Daikin (2013) *Major Source Operating Permit*, Daikin America, Alabama Department of Environmental Management, August 1, 2013. http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0. (p. 11-1).

Honeywell (2012) *Part 70 Operating Permit*, Geismar Plant, Honeywell International Inc., Louisiana, Louisiana Department of Environmental Quality, Page 13, January 28, 2011. https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

Honeywell (2011) *Part 70 Operating Permit*, Baton Rouge Plant Honeywell International Inc., Louisiana Department of Environmental Quality, Page 25, October 16, 2012. https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

ICI Americas (1993) *New Permit, KLEA – 134a Plant*, ICI Americas, St. Gabriel, Louisiana, Louisiana Department of Environmental Quality, Page 44, May 28, 1993. https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L.

Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896. Available from www.ipcc.ch. The AR6 GWPs are listed in Table 7.SM.7, which appears on page 16 of the Supplementary Material.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. The GWPs are listed in Table 8.A.1 of Appendix 8.A: Lifetimes, Radiative Efficiencies and Metric Values, which appears on pp. 731-737 of Chapter 8, "Anthropogenic and Natural Radiative Forcing."

IPCC (2007) *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

McKenna (2022) *A 3M Plant in Illinois Was the Country's Worst Emitter of a Climate-Killing 'Immortal' Chemical in 2021*, Phil McKenna, Inside Climate News, December 29, 2022. [3M Cordova IL facility.] https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

Perkins (1982) Perkins, B. L., *Evaluation of Environmental Control Technologies for Commercial Nuclear Fuel Conversion (UF_6) Facilities*, LA-9397-MS, October 1982 [030000442.pdf].

Rand (2007) *2004-2006 SF_6 Data Summary*, Project Memorandum Prepared by D. Knopman and K. Smythe, RAND Corporation, for the National Electrical Manufacturers Association, June 2007.

SRI Consulting (2004) *Chemical Economics Handbook (CEH) Market Research Report: Fluorocarbons*, R. Will, A. Kishi, S. Schlag. SRI Consulting, 2004.

U.S. EPA (2008) Survey of Producers of HFCs, PFCs, SF_6 and NF_3, 2008. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023a) GHGRP Data Relevant to the AIM Act, Greenhouse Gas Reporting Program. https://www.epa.gov/ghgreporting/ghgrp-data-relevant-aim-act. Last accessed 11/16/2023.

U.S. EPA (2023b) Vintaging Model for HFCs. 2023. Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023c) Estimated layer-weighted substrate production by the semiconductor industry. Office of Atmospheric Programs, Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. EPA (2023d) SF_6 Consumption by Users. 2023. SF_6 consumption for 3 industries, Electric Transmission and Distribution, Semiconductor Manufacturing, and Magnesium Production. Office of Atmospheric Protection, U.S. Environmental Protection Agency.

U.S. EPA (2015) Greenhouse Gas Reporting Program Report Verification. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

U.S. EPA (1995) *Protocol for Equipment Leak Emission Estimates*. Office of Air and Radiation, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Publication No. EPA-453/R-95-017. November 1995.

Vollmer et al. (2019) Vollmer, M. K., Bernard, F., Mitrevski, B., Steele, L. P., Trudinger, C. M., Reimann, S., Langenfelds, R. L., Krummel, P. B., Fraser, P. J., Etheridge, D. M., Curran, M. A. J., and Burkholder, J. B.: Abundances, emissions, and loss processes of the long-lived and potent greenhouse gas octafluorooxolane

(octafluorotetrahydrofuran, c-C4F8O) in the atmosphere, Atmos. Chem. Phys., 19, 3481–3492, https://doi.org/10.5194/acp-19-3481-2019 , 2019..

Carbon Dioxide Consumption

ARI (1990 through 2010) *CO_2 Use in Enhanced Oil Recovery.* Deliverable to ICF International under Task Order 102, July 15, 2011.

ARI (2007) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2007.

ARI (2006) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, D.C. April 20-21, 2006.

Broadhead (2003) Personal communication. Ron Broadhead, Principal Senior Petroleum Geologist and Adjunct faculty, Earth and Environmental Sciences Department, New Mexico Bureau of Geology and Mineral Resources, and Robin Petrusak, ICF International. September 5, 2003.

COGCC (2014) Monthly CO_2 Produced by County (1999-2009). Available online at: http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyCO2ProdByCounty. Accessed October 2014.

Denbury Resources Inc. (2002 through 2010) Annual Report: 2001 through 2009, Form 10-K. Available online at: http://www.denbury.com/investor-relations/SEC-Filings/SEC-Filings-Details/default.aspx?FilingId=9823015. Accessed September 2014.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

New Mexico Bureau of Geology and Mineral Resources (2006) Natural Accumulations of Carbon Dioxide in New Mexico and Adjacent Parts of Colorado and Arizona: Commercial Accumulation of CO_2. Available online at: http://geoinfo.nmt.edu/staff/broadhead/CO2.html#commercial.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

U.S. Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart PP -National Level CO_2 Transferred for Food & Beverage Applications for Calendar Years 2010 through 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Phosphoric Acid Production

EFMA (2000) "Production of Phosphoric Acid." *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry.* Booklet 4 of 8. European Fertilizer Manufacturers Association. Available online at: http://www.efma.org/Publications/BAT%202000/Bat04/section04.asp.

Florida Institute of Phosphate Research (FIPR) (2003a) "Analyses of Some Phosphate Rocks." Facsimile Gary Albarelli, Florida Institute of Phosphate Research, Bartow, Florida, to Robert Lanza, ICF International. July 29, 2003.

FIPR (2003b) Florida Institute of Phosphate Research. Personal communication between Michael Lloyd (Laboratory Manager, FIPR, Bartow, Florida) aand Robert Lanza (ICF International) on August 2003.

Golder Associates and M3 Engineering, *Bayovar 12 Phosphate Project: NI 43-101 Updated Pre-Feasibility Study*, Issued June 28, 2016. Available at: https://www.sec.gov/Archives/edgar/data/1471603/000121716016000634/focusjune2016bayovar_techrep.htm. Accessed on October 7, 2020.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

NCDENR (2013) North Carolina Department of Environment and Natural Resources, Title V Air Permit Review for PCS Phosphate Company, Inc. – Aurora. Available online at: http://www.ncair.org/permits/permit_reviews/PCS_rev_08282012.pdf. Accessed on January 25, 2013.

United States Environmental Protection Agency (EPA) (2023) Greenhouse Gas Reporting Program. Review of Reported Facility Level Data under Subpart Z -Annual Phosphoric Acid Production from Phosphate Rock for Calendar Year 2022. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023) *Mineral Commodity Summaries: Phosphate Rock 2023*. January 2023. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information

USGS (2022) *Mineral Commodity Summaries: Phosphate Rock 2022*. January 2022. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information

USGS (2021a) *Mineral Commodity Summaries: Phosphate Rock 2021*. January 2021. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2021b) Personal communication between Stephen Jasinski (USGS) and Amanda Chiu (EPA) on August 25, 2021.

USGS (2020) *Mineral Commodity Summaries: Phosphate Rock 2020*. January 2020. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2019a) *Mineral Commodity Summaries: Phosphate Rock 2019*. February 2019. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2019b) Communication between Stephen Jasinski (USGS) and John Steller (EPA) on November 15, 2019.

USGS (2018) *Mineral Commodity Summaries: Phosphate Rock 2018*. January 2018. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2017) *Mineral Commodity Summaries: Phosphate Rock 2017*. January 2017. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (2016) *Mineral Commodity Summaries: Phosphate Rock 2016*. January 2016. U.S. Geological Survey, Reston, VA. Available online at: https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information.

USGS (1994 through 2015b) *Minerals Yearbook*. *Phosphate Rock Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2012) Personal communication between Stephen Jasinski (USGS) and Mausami Desai (EPA) on October 12, 2012.

Iron and Steel Production and Metallurgical Coke Production

American Coke and Coal Chemicals Institute (ACCCI) (2021) *U.S. Coke Plants as of November 2021,* ACCCI, Washington, D.C. November 2021.

American Iron and Steel Institute (AISI) (2004 through 2023) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

Carroll (2017) Personal communication, Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute and John Steller, U.S. Environmental Protection Agency, November 2017.

Carroll (2016) Personal communication, Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute and Mausami Desai, U.S. Environmental Protection Agency, December 2016.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom996 pp.IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1995) "Volume 3: Greenhouse Gas Inventory Reference Manual. Table 2-2." *IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. IPCC WG1 Technical Support Unit, United Kingdom.

RTI (2024) Expert judgment, RTI International. April 2024.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Steiner (2008) Personal communication, Bruce Steiner, Technical Consultant with the American Iron and Steel Institute and Mausami Desai, U.S. Environmental Protection Agency, November 2008.

Tuck (2023a) Personal communication, Cris Tuck, Commodity Specialist, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency, January 24, 2023.

Tuck (2023b) Personal communication, Candice Tuck, Commodity Specialist, U.S. Geological Survey and Amanda Chiu, U.S. Environmental Protection Agency, November 30, 2023.

United States Department of Energy (DOE) (2000) *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. Office of Industrial Technologies, U.S. Department of Energy. August 2000. DOE/EE-0229.EIA.

United States Energy Information Administration (EIA) (1998 through 2019) *Quarterly Coal Report: October-December*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

U.S. EIA (2021 through 2023) *Quarterly Coal Report: January – March,* Energy Information Administration, U.S. Department of Energy. Washington, D.C.

U.S. EIA (2020) *Natural Gas Annual 2019.* Energy Information Administration, U.S. Department of Energy. Washington, D.C. September 2020.

U.S. EIA (2017b) *Monthly Energy Review*, *December 2017*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

U.S. EIA (1992) Coal and lignite production. *EIA State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

United States Environmental Protection Agency (EPA) (2023). Greenhouse Gas Reporting Program. Dataset as of August 18, 2023. Available online at: https://ghgdata.epa.gov/ghgp/.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

United States Geological Survey (USGS) (2023a) *2022 Mineral Commodities Summaries: Iron and Steel.* U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *2021 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2022) *2020 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2021a) *2021 Mineral Commodities Summaries: Iron and Steel.* U.S. Geological Survey, Reston, VA. January 2021.

USGS (2021b) *2019 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2020a) *2018 USGS Minerals Yearbook – Iron and Steel Scrap (tables-only release)*. U.S. Geological Survey, Reston, VA.

USGS (2020b) *2017 USGS Minerals Yearbook – Iron and Steel*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2020) *USGS Minerals Yearbook – Iron and Steel Scrap.* U.S. Geological Survey, Reston, VA.

Ferroalloy Production

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Onder, H., and E.A. Bagdoyan (1993) Everything You've Always Wanted to Know about Petroleum Coke. Allis Mineral Systems.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

United States Geological Survey (USGS) (2023a) *Mineral Industry Survey: Silicon in June 2023*. U.S. Geological Survey, Reston, VA. September 2023.

USGS (2023b) *2022 Mineral Commodity Summaries: Silicon.* U.S. Geological Survey, Reston, VA. January 2023.

USGS (2022a) *2021 Minerals Yearbook: Silicon (*tables-only release). U.S. Geological Survey, Reston, VA. September 2022.

USGS (2022b) *2020 Minerals Yearbook: Ferroalloys (tables-only release)*. U.S. Geological Survey, Reston, VA. May 2023.

USGS (2022c) *2021 Mineral Commodity Summaries*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021) *2020 Mineral Commodity Summaries: Silicon*. U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020) *2019 Mineral Commodity Summaries: Silicon*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2013a) *2013 Minerals Yearbook: Chromium*. U.S. Geological Survey, Reston, VA. March 2016.

USGS (1996 through 2022) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

Aluminum Production

EPA (2023) Greenhouse Gas Reporting Program (GHGRP). Envirofacts, Subpart: F Aluminum Production. Available online at: https://www.epa.gov/enviro/greenhouse-gas-subpart-f

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds.)]. Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USGS (2023) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2022) Mineral Commodity Summaries 2022. U.S. Geological Survey, Reston VA.

USGS (2021) *2020 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2021) *2019 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2020) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2020) Mineral Industry Surveys: Aluminum in December 2020. U.S. Geological Survey, Reston VA. December 2020

USGS (2020) *2019 Mineral Commodity Summaries: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2019) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2018) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2017) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2016) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2015) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2014) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2013) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2012) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2011) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2010) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2009) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2008) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2007) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2006) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2005) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2004) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2003) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2002) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2001) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2000) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1999) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1998) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1997) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1996) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1994) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1993) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1992) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1991) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1990) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Magnesium Production and Processing

ARB (2015) "Magnesium casters successfully retool for a cleaner future." California Air Resources Board News Release. Release # 15-07. February 5, 2015. Accessed October 2017. Available online at: https://www.arb.ca.gov/newsrel/newsrelease.php?id=704.

Bartos S., C. Laush, J. Scharfenberg, and R. Kantamaneni (2007) "Reducing greenhouse gas emissions from magnesium die casting." *Journal of Cleaner Production*, 15: 979-987, March.

EPA (2020) Envirofacts. Greenhouse Gas Reporting Program (GHGRP), Subpart T: Magnesium Production and Processing. Available online at: https://www.epa.gov/enviro/greenhouse-gas-customized-search. Accessed on October 2020.

EPA (2015) *Greenhouse Gas Reporting Program Report Verification*. Available online at https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Gjestland, H. and D. Magers (1996) "Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry." #13, *1996 Annual Conference Proceedings*, International Magnesium Association. Ube City, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kramer Deborah A. (2000) "Magnesium" U.S. Geological Survey *Minerals Yearbook* – 2000.

RAND (2002) RAND Environmental Science and Policy Center, "Production and Distribution of SF_6 by End-Use Applications" Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. San Diego, CA. November 21-22, 2002.

USGS (1995 through 2023) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis.

USGS (2010b) *Mineral Commodity Summaries: Magnesium Metal*. U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2010-mgmet.pdf.

USGS (2005b) Personal Communication between Deborah Kramer of the USGS and Jeremy Scharfenberg of ICF Consulting.

Lead Production

Dutrizac, J.E., V. Ramachandran, and J.A. Gonzalez (2000) *Lead-Zinc 2000*. The Minerals, Metals, and Materials Society.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Morris, D., F.R. Steward, and P. Evans (1983) *Energy Efficiency of a Lead Smelter.* Energy 8(5):337-349.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Sjardin, M. (2003) *CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Ullman (1997) *Ullman's Encyclopedia of Industrial Chemistry: Fifth Edition.* Volume A5. John Wiley and Sons.

United States Geological Survey (USGS) (2023a) *2022 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2023.

USGS (2023b) *2020 Minerals Yearbook, Lead – Advance Data Release*. U.S. Geological Survey, Reston, VA. July 2023.

USGS (2023c) *2022 Mineral Industries Surveys: Lead in September 2022.* U.S. Geological Survey, Reston, VA. December 2022.

USGS (2022a) *2019 Minerals Yearbook, Lead – Advance Data Release*. U.S. Geological Survey, Reston, VA. October 2022.

USGS (2022b) *2021 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021a) *2017 Minerals Yearbook, Lead – Advance Release*. U.S. Geological Survey, Reston, VA. July 2021.

USGS (2021b) *2020 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. February 2021.

USGS (2020) *2019 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2020.

USGS (2019) *2018 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2019.

USGS (2018) *2017 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2018.

USGS (2017) *2016 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2016) *2015 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2016.

USGS (2015) *2014 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA. January 2015.

USGS (2014) *2013 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2014.

USGS (1994 through 2013) *Minerals Yearbook: Lead Annual Report.* U.S. Geological Survey, Reston, VA..

Zinc Production

American Zinc Recycling (AZR) (2021) Summary of Company History. Available online at https://azr.com/our-history/. Accessed on March 16, 2021.

AZR (2020) Personal communication. Erica Livingston, American Zinc Recycling and Amanda Chiu, U.S. Environmental Protection Agency. October 29, 2020.

American Zinc Products (AZP) (2021) American Zinc Products Marks First Anniversary of Zinc Production. Available online at https://americanzincproducts.com/american-zinc-products-marks-first-anniversary-of-zinc-production/. Accessed on March 1, 2022.

Befesa (2023) Personal communication. Eric Hunsberger, Befesa Zinc US Inc. and Amanda Chiu, U.S. Environmental Protection Agency. September 19, 2023.

Befesa (2022) Personal communication. Eric Hunsberger, Befesa Zinc US Inc. and Amanda Chiu, U.S. Environmental Protection Agency. November 8, 2022.

Horsehead Corp. (2016) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2015. Available online at: https://www.sec.gov/Archives/edgar/data/1385544/000119312516725704/d236839d10k.htm. Submitted on January 25, 2017.

Horsehead Corp. (2015) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2014. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000138554415000005/zinc-2014123110k.htm. Submitted on March 2, 2015.

Horsehead Corp. (2014) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2013. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000138554414000003/zinc-2013123110k.htm. Submitted on March 13, 2014.

Horsehead Corp. (2013) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2012. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000119312513110431/0001193125-13-110431-index.htm. Submitted March 18, 2013.

Horsehead Corp. (2012a) Form 10-K, Annual Report for the Fiscal Year Ended December 31, 2011. Available online at: http://www.sec.gov/Archives/edgar/data/1385544/000119312512107345/d293011d10k.htm. Submitted on March 9, 2012.

Horsehead Corp. (2012b) *Horsehead's New Zinc Plant and its Impact on the Zinc Oxide Business.* February 22, 2012. Available online at: http://www.horsehead.net/downloadAttachmentNDO.php?ID=118. Accessed on September 10, 2015.

Horsehead Corp. (2011) 10-K Annual Report for the Fiscal Year Ended December 31, 2010. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 16, 2011.

Horsehead Corp. (2010a) 10-K Annual Report for the Fiscal Year Ended December 31, 2009. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 16, 2010.

Horsehead Corp. (2010b) *Horsehead Holding Corp. Provides Update on Operations at its Monaca, PA Plant.* July 28, 2010. Available online at: http://www.horsehead.net/pressreleases.php?showall=no&news=&ID=65.

Horsehead Corp (2009) 10-K Annual Report for the Fiscal Year Ended December 31, 2008. Available online at: https://www.sec.gov/Archives/edgar/data/1385544/000095015209002674/l35087ae10vk.htm. Submitted on March 16, 2009.

Horsehead Corp (2008) 10-K Annual Report for the Fiscal Year Ended December 31, 2007. Available online at: http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on March 31, 2008.

Horsehead Corp (2007) Registration Statement (General Form) S-1. Available online at http://google.brand.edgar-online.com/default.aspx?sym=zinc. Submitted on April 13, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Nyrstar (2017) 2016 Clarksville Fact Sheet. Available online at: http://www.nyrstar.com/~/media/Files/N/Nyrstar/operations/melting/fact-sheet-clarksville-en.pdf. Accessed on September 27, 2017.

PIZO (2021) Personal communication. Thomas Rheaume, Arkansas Department of Energy and Environment and Amanda Chiu, U.S. Environmental Protection Agency. February 16, 2021.

PIZO (2012) Available online at http://pizotech.com/index.html. Accessed on October 10, 2012.

Recycling Today (2020) "AZR to restart for zinc recycling plant in North Carolina." March 6, 2020. https://www.recyclingtoday.com/article/american-zinc-recycling-restarting-north-carolina-plant-2020/. Accessed October 10, 2020.

Recycling Today (2017) "Horsehead announces corporate name change to American Zinc Recycling." May 3, 2017. https://www.recyclingtoday.com/article/horsehead-changes-name-american-zinc-recycling/. Accessed September 19, 2022.

Steel Dust Recycling (SDR) (2023) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. September 20 and 25, 2023.

SDR (2022) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. October 10, 2022.

SDR (2021) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Amanda Chiu, U.S. Environmental Protection Agency. January 8, 2021.

SDR (2018) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and John Steller, U.S. Environmental Protection Agency. October 25, 2018.

SDR (2017) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and John Steller, U.S. Environmental Protection Agency. January 26, 2017.

SDR (2015) Personal communication. Jeremy Whitten, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. September 22, 2015.

SDR (2014) Personal communication. Art Rowland, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. December 9, 2014.

SDR (2013) Available online at http://steeldust.com/home.htm. Accessed on October 29, 2013.

SDR (2012) Personal communication. Art Rowland, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. October 5, 2012.

Sjardin (2003) CO_2 *Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

United States Environmental Protection Agency (EPA) (1992) "Applications Analysis Report: Horsehead Resource Development Company Inc., Flame Reactor Technology" EPA/540/A5-91/005. May 1992.

United States Geological Survey (USGS) (2023) *2023 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2023. Available online at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-zinc.pdf

USGS (2022) *2022 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2022.

USGS (2021) *2021 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2021.

USGS (2020) *2020 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2020.

USGS (2019) *2019 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2019.

USGS (2018) *2018 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2018.

USGS (2017) *2017 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2017.

USGS (2016) *2016 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2016.

USGS (2015) *2015 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2015.

USGS (1994 through 2014) *Minerals Yearbook: Zinc Annual Report.* U.S. Geological Survey, Reston, VA.

Viklund-White (2000) *The use of LCA for the environmental evaluation of the recycling of galvanized steel*. ISIJ International, Vol. 40. No. 3, pp 292-299.

Electronics Industry

Burton, C.S., and R. Beizaie (2001) "EPA's PFC Emissions Model (PEVM) v. 2.14: Description and Documentation" prepared for Office of Global Programs, U. S. Environmental Protection Agency, Washington, DC. November 2001.

Citigroup Smith Barney (2005) *Global Supply/Demand Model for Semiconductor*s. March 2005.

DisplaySearch (2010) DisplaySearch Q4'09 Quarterly FPD Supply/Demand and Capital Spending Report. DisplaySearch, LLC.

Doering, R. and Nishi, Y (2000) "Handbook of Semiconductor Manufacturing Technology", Marcel Dekker, New York, USA, 2000.

EPA (2023) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021*. U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-23-002.

EPA (2010) *Technical Support Document for Process Emissions from Electronics Manufacture (e.g., Micro-Electro-Mechanical Systems, Liquid Crystal Displays, Photovoltaics, and Semiconductors)*. U.S. Environmental Protection Agency, Washington, DC.

EPA (2006) *Uses and Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector.* U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-06-901.

EPA Greenhouse Gas Reporting Program (GHGRP) Envirofacts. Subpart I: Electronics Manufacture. Available online at: https://enviro.epa.gov/facts/ghg/search.html.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

ITRS (2007, 2008, 2011, 2013) *International Technology Roadmap for Semiconductors: 2006 Update*, January 2007; *International Technology Roadmap for Semiconductors: 2007 Edition,* January 2008*; International Technology Roadmap for Semiconductors: 2011, January 2012; Update, International Technology Roadmap for*

Semiconductors: 2013 Edition, Available online at: https://www.semiconductors.org/resources/2007-international-technology-roadmap-for-semiconductors-itrs/. These and earlier editions and updates are available online at: https://www.semiconductors.org/resources/?fwp_resource_types=utilization-reports&fwp_paged=2. Information about the number of interconnect layers for years 1990–2010 is contained in Burton and Beizaie, 2001. PEVM is updated using new editions and updates of the ITRS, which are published annually.

Platzer, Michaela D. (2015) *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support*. Congressional Research Service. January 27, 2015. https://fas.org/sgp/crs/misc/R42509.pdf.

SEMI – Semiconductor Equipment and Materials Industry (2021) *World Fab Forecast, June 2021 Edition.*

SEMI - Semiconductor Equipment and Materials Industry (2018) *World Fab Forecast*, *June 2018 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2017) *World Fab Forecast*, *August 2018 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2016) *World Fab Forecast*, *May 2017 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2013) *World Fab Forecast*, *May 2013 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2012) *World Fab Forecast*, *August 2012 Edition*.

Semiconductor Industry Association (SIA) (2009-2011) STATS: SICAS Capacity and Utilization Rates Q1-Q4 2008, Q1-Q4 2009, Q1-Q4 2010. Available online at: http://www.semiconductors.org/industry_statistics/semiconductor_capacity_utilization_sicas_reports/.

United States Census Bureau (USCB) (2011, 2012, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) *Historical Data: Quarterly Survey of Plant Capacity Utilization*. Available online at: https://www.census.gov/programs-surveys/qpc.html.

VLSI Research, Inc. (2012) Worldwide Silicon Demand. August 2012.

Substitution of Ozone Depleting Substances

EPA (2023a) Summary of Updates to the Unitary Air-conditioning End-uses in the Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023b) Summary of Updates to the Window Units End-use in the Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023c) Proposed Addition of Small and Large Ductless Mini-Split and Multi-Split Air Conditioning End-uses to U.S. EPA's Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2023d) Proposed Updates to the Streaming Agent End-uses in U.S. EPA's Vintaging Model. Prepared for U.S. EPA's Stratospheric Protection Division by ICF under EPA Contract Number 68HERH19D0029.

EPA (2018) EPA's Vintaging Model of ODS Substitutes: A Summary of the 2017 Peer Review. Office of Air and Radiation. Document Number EPA-400-F-18-001. Available online at: https://www.epa.gov/sites/production/files/2018-09/documents/epas-vintaging-model-of-ods-substitutes-peer-review-factsheet.pdf.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen,

M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Electrical Equipment

CARB (2023). *California Greenhouse Gas Emission Inventory – 2023 Edition.* Accessed March 2024. Available online at: https://ww2.arb.ca.gov/ghg-inventory-data.

EPA (2022) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020*. EPA 430-R-22-003. Available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.

Harnisch and Eisenhauer, "Natural CF_4 and SF_6 on Earth," GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.13, PAGES 2401-2404, JULY 1, 1998. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/98GL01779.

HIFLD (2022) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2021. Accessed September 2023. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::transmission-lines/explore?location=38.924381%2C-122.290494%2C4.78 .

HIFLD (2021) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2021. Accessed September 2022. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines.

HIFLD (2020) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2020. Accessed October 2021. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines/explore?showTable=true.

HIFLD (2019) Federal Energy Regulatory Commission. Homeland Infrastructure Foundation-Level Data (HIFLD). 2019. Accessed March 2021. Available online at: https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines.

Hu, L., Ottinger, D., Bogle, S., Montzka, S., DeCola, P., Dlugokencky, E., Andrews, A., Thoning, K., Sweeney, C., Dutton, G., Aepli, L., and Crotwell, A. (2022) "Declining, seasonal-varying emissions of sulfur hexafluoride from the United States point to a new mitigation opportunity." *EGUsphere* [preprint]. Available online at: https://doi.org/10.5194/egusphere-2022-862.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

Levin et al. (2010) "The Global SF_6 Source Inferred from Long-term High Precision Atmospheric Measurements and its Comparison with Emission Inventories." *Atmospheric Chemistry and Physics*, 10: 2655–2662.

Middleton, B. (2000) *Cold Weather Applications of Gas Mixture (SF_6/N_2, SF_6/CF_4) Circuit Breakers: A User Utility's Perspective* [Conference Presentation]. The U.S. Environmental Protection Agency's Conference on SF_6 and the Environment: Emission Reduction Strategies, San Diego, CA, United States. Available online at: https://www.epa.gov/sites/default/files/2016-02/documents/conf00_middleton.pdf

O'Connell, P., F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, J.P. Tailebois (2002) *SF_6 in the Electric Industry, Status 2000,* CIGRE. February 2002.

Ottinger D, Averyt, M. & Harris, D. (2014). *Trends in emissions of fluorinated GHGs reported under the Greenhouse Gas Reporting Program: Patterns and potential causes*. Submitted to the Seventh International Symposium on Non-CO_2 Greenhouse Gases (NCGG-7), Amsterdam, Netherlands.

RAND (2004) "Trends in SF_6 Sales and End-Use Applications: 1961-2003," Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. RAND Environmental Science and Policy Center, Scottsdale, AZ. December 1-3, 2004.

UDI (2017) *2017 UDI Directory of Electric Power Producers and Distributors, 125th Edition*, Platts.

UDI (2013) *2013 UDI Directory of Electric Power Producers and Distributors,121st Edition*, Platts.

UDI (2010) *2010 UDI Directory of Electric Power Producers and Distributors, 118th Edition*, Platts.

UDI (2007) *2007 UDI Directory of Electric Power Producers and Distributors, 115th Edition*, Platts.

UDI (2004) *2004 UDI Directory of Electric Power Producers and Distributors, 112th Edition*, Platts.

UDI (2001) *2001 UDI Directory of Electric Power Producers and Distributors, 109th Edition*, Platts.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

SF_6 and PFCs from Other Product Use

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Workman, R.L. et al. Particle Data Group). Prog. Theor. Exp. Phys. 2022, 083C01. Available online at: https://pdg.lbl.gov/2022/reviews/rpp2022-rev-particle-detectors-accel.pdf

U.S. Department of Energy (DOE). 2022. Federal Energy Management Program (FEMP). Available online at: https://www.energy.gov/femp/federal-comprehensive-annual-energy-reporting-requirements.

Nitrous Oxide from Product Use

CGA (2003) "CGA Nitrous Oxide Abuse Hotline: CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. November 3, 2003.

CGA (2002) "CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. March 25, 2002.

Heydorn, B. (1997) "Nitrous Oxide—North America." *Chemical Economics Handbook*, SRI Consulting. May 1997.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Ottinger (2021) Personal communication. Deborah Ottinger, U.S. Environmental Protection Agency and Amanda Chiu, U.S. Environmental Protection Agency. January 7, 2021.

RTI (2023) Expert judgment, RTI International. March 30, 2023.

Tupman, M. (2002) Personal communication. Martin Tupman, Airgas Nitrous Oxide and Laxmi Palreddy, ICF International. July 3, 2002.

Industrial Processes and Product Use Sources of Precursor Greenhouse Gases

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 - 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) EPA's Emissions Inventory System (EIS) to National Inventory Report (NIR) Mapping file EIS_NIR_mapping.xlsx. U.S. Environmental Protection Agency. Washington, D.C."

EPA (2023c) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Agriculture

Enteric Fermentation

Archibeque, S. (2011) Personal Communication. Shawn Archibeque, Colorado State University, Fort Collins, Colorado and staff at ICF International.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986) Methane Production by Domestic Animals, Wild Ruminants, Other Herbivores, Fauna, and Humans. Tellus, 38B:271-284.

Donovan, K. (1999) Personal Communication. Kacey Donovan, University of California at Davis and staff at ICF International.

Donovan, K. and L. Baldwin. (1999) "Results of the AAMOLLY Model Runs for the Enteric Fermentation Model"; University of California, Davis, 1999.

Doren, P.E., J. F. Baker, C. R. Long and T. C. Cartwright (1989) Estimating Parameters of Growth Curves of Bulls, J Animal Science 67:1432-1445.

Enns, M. (2008) Personal Communication. Dr. Mark Enns, Colorado State University and staff at ICF International.

EPA (2002) Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis, U.S. Greenhouse Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

ERG (2021) Updated Other Animal Population Distribution Methodology. ERG, Lexington, MA.

ERG (2016) Development of Methane Conversion Rate Scaling Factor and Diet-Related Inputs to the Cattle Enteric Fermentation Model for Dairy Cows, Dairy Heifers, and Feedlot Animals. ERG, Lexington, MA. December 2016.

Galyean and Gleghorn (2001) Summary of the 2000 Texas Tech University Consulting Nutritionist Survey. Texas Tech University. Available online at http://www.depts.ttu.edu/afs/burnett_center/progress_reports/bc12.pdf. June 2009.

Holstein Association (2010) History of the Holstein Breed (website). Available online at: http://www.holsteinusa.com/holstein_breed/breedhistory.html. Accessed September 2010.

ICF (2006) Cattle Enteric Fermentation Model: Model Documentation. Prepared by ICF International for the Environmental Protection Agency. June 2006.

ICF (2003) Uncertainty Analysis of 2001 Inventory Estimates of Methane Emissions from Livestock Enteric Fermentation in the U.S. Memorandum from ICF International to the Environmental Protection Agency. May 2003.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Johnson, D. (2002) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and ICF International.

Johnson, D. (1999) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and David Conneely, ICF International.

Kebreab E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. J. Anim. Sci. 86: 2738-2748.

Lippke, H., T. D. Forbes, and W. C. Ellis. (2000) Effect of supplements on growth and forage intake by stocker steers grazing wheat pasture. J. Anim. Sci. 78:1625-1635.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association, July 19, 2011.

Pinchak, W.E., D. R. Tolleson, M. McCloy, L. J. Hunt, R. J. Gill, R. J. Ansley, and S. J. Bevers (2004) Morbidity effects on productivity and profitability of stocker cattle grazing in the southern plains. J. Anim. Sci. 82:2773-2779.

Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith (2003) Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. J. Anim. Sci. 81:984-996.

Preston, R.L. (2010) What's The Feed Composition Value of That Cattle Feed? Beef Magazine, March 1, 2010. Available at: http://beefmagazine.com/nutrition/feed-composition-tables/feed-composition-value-cattle--0301.

Skogerboe, T. L., L. Thompson, J. M. Cunningham, A. C. Brake, V. K. Karle (2000) The effectiveness of a single dose of doramectin pour-on in the control of gastrointestinal nematodes in yearling stocker cattle. Vet. Parasitology 87:173-181.

Soliva, C.R. (2006) Report to the attention of IPCC about the data set and calculation method used to estimate methane formation from enteric fermentation of agricultural livestock population and manure management in Swiss agriculture. On behalf of the Federal Office for the Environment (FOEN), Berne, Switzerland.

U.S. Department of Agriculture (USDA) (2023) Quick Stats: Agricultural Statistics Database. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at http://quickstats.nass.usda.gov/. Accessed May-June 2023.

USDA (2022) Economic Research Service "Supply and allocation of milk fat and skim solids by product". Available online at: https://www.ers.usda.gov/data-products/dairy-data/. Accessed May 2023.

USDA (2021) Economic Research Service Dairy Data. Available online at: https://www.ers.usda.gov/data-products/dairy-data/. Accessed May 2021.

USDA (2019) *1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: https://www.nass.usda.gov/AgCensus/index.php. May 2019.

USDA (1996) Beef Cow/Calf Health and Productivity Audit (CHAPA): Forage Analyses from Cow/Calf Herds in 18 States. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at http://www.aphis.usda.gov/vs/ceah/cahm. March 1996.

USDA:APHIS:VS (2010) Beef 2007–08, Part V: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA–APHIS–VS, CEAH. Fort Collins, CO.

USDA:APHIS:VS (2002) Reference of 2002 Dairy Management Practices. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1998) Beef '97, Parts I-IV. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/animal_health/nahms/beefcowcalf/index.shtml#beef97.

USDA:APHIS:VS (1996) Reference of 1996 Dairy Management Practices. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1994) Beef Cow/Calf Health and Productivity Audit. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

USDA:APHIS:VS (1993) Beef Cow/Calf Health and Productivity Audit. USDA–APHIS–VS, CEAH. Fort Collins, CO. August 1993. Available online at http://www.aphis.usda.gov/vs/ceah/cahm.

Vasconcelos and Galyean (2007) Nutritional recommendations of feedlot consulting nutritionists: The 2007 Texas Tech University Study. J. Anim. Sci. 85:2772-2781.

Manure Management

ASAE (1998) ASAE Standards 1998, 45th Edition. American Society of Agricultural Engineers. St. Joseph, MI.

Bryant, M.P., V.H. Varel, R.A. Frobish, and H.R. Isaacson (1976) In H.G. Schlegel (ed.)]; Seminar on Microbial Energy Conversion. E. Goltz KG. Göttingen, Germany.

Bush, E. (1998) Personal communication with Eric Bush, Centers for Epidemiology and Animal Health, U.S. Department of Agriculture regarding National Animal Health Monitoring System's (NAHMS) Swine '95 Study.

EPA (2023) AgSTAR Anaerobic Digester Database. Available online at: https://www.epa.gov/agstar/livestock-anaerobic-digester-database. Accessed August 2023.

EPA (2008) Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type Managing Manure with Biogas Recovery Systems.

EPA (2005) National Emission Inventory—Ammonia Emissions from Animal Agricultural Operations, Revised Draft Report. U.S. Environmental Protection Agency. Washington, D.C. April 22, 2005.

EPA (2002a) Development Document for the Final Revisions to the National Pollutant Discharge Elimination System (NPDES) Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (CAFOS). U.S. Environmental Protection Agency. EPA-821-R-03-001. December 2002.

EPA (2002b) Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations. U.S. Environmental Protection Agency. EPA-821-R-03-004. December 2002.

EPA (1992) Global Methane Emissions from Livestock and Poultry Manure, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

ERG (2023) Summary of Data Processing and Proposed Integration of 2018 Beef Feedlot and Poultry Waste Management System Data into the Manure Management Greenhouse Gas Inventory. Memorandum to EPA from ERG, December 2023.

ERG (2021) Updated Other Animal Population Distribution Methodology. Memorandum to EPA from ERG.

ERG (2019) "Incorporation of USDA 2016 ARMS Dairy Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG, December 2019.

ERG (2018) "Incorporation of USDA 2009 ARMS Swine Data into the Manure Management Greenhouse Gas Inventory." Memorandum to USDA OCE and EPA from ERG, November 2018.

ERG (2010a) "Typical Animal Mass Values for Inventory Swine Categories." Memorandum to EPA from ERG. July 19, 2010.

ERG (2010b) Telecon with William Boyd of USDA NRCS and Cortney Itle of ERG Concerning Updated VS and Nex Rates. August 8, 2010.

ERG (2010c) "Updating Current Inventory Manure Characteristics new USDA Agricultural Waste Management Field Handbook Values." Memorandum to EPA from ERG. August 13, 2010.

ERG (2008) "Methodology for Improving Methane Emissions Estimates and Emission Reductions from Anaerobic Digestion System for the 1990-2007 Greenhouse Gas Inventory for Manure Management." Memorandum to EPA from ERG. August 18, 2008.

ERG (2003a) "Methodology for Estimating Uncertainty for Manure Management Greenhouse Gas Inventory." Contract No. GS-10F-0036, Task Order 005. Memorandum to EPA from ERG, Lexington, MA. September 26, 2003.

ERG (2003b) "Changes to Beef Calves and Beef Cows Typical Animal Mass in the Manure Management Greenhouse Gas Inventory." Memorandum to EPA from ERG, October 7, 2003.

ERG (2001) Summary of development of MDP Factor for methane conversion factor calculations. ERG, Lexington, MA. September 2001.

ERG (2000a) Calculations: Percent Distribution of Manure for Waste Management Systems. ERG, Lexington, MA. August 2000.

ERG (2000b) Discussion of Methodology for Estimating Animal Waste Characteristics (Summary of Bo Literature Review). ERG, Lexington, MA. June 2000.

Groffman, P.M., R. Brumme, K. Butterbach-Bahl, K.E. Dobbie, A.R. Mosier, D. Ojima, H. Papen, W.J. Parton, K.A. Smith, and C. Wagner-Riddle (2000) "Evaluating annual nitrous oxide fluxes at the ecosystem scale." Global Biogeochemical Cycles, 14(4):1061-1070.

Hashimoto, A.G. (1984) "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." Agricultural Wastes, 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen (1981) "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." Agricultural Wastes, 3:241-256.

Hill, D.T. (1984) "Methane Productivity of the Major Animal Types." Transactions of the ASAE, 27(2):530-540.

Hill, D.T. (1982) "Design of Digestion Systems for Maximum Methane Production." Transactions of the ASAE, 25(1):226-230.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Morris, G.R. (1976) Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation. M.S. Thesis. Cornell University.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.

Ott, S.L. (2000) Dairy '96 Study. Stephen L. Ott, Animal and Plant Health Inspection Service, U.S. Department of Agriculture. June 19, 2000.

Robertson, G. P. and P. M. Groffman (2015) Nitrogen transformations. Soil Microbiology, Ecology, and Biochemistry, pages 421-446. Academic Press, Burlington, Massachusetts, USA.

Safley, L.M., Jr. (2000) Personal Communication. Deb Bartram, ERG and L.M. Safley, President, Agri-Waste Technology. June and October 2000.

Sweeten, J. (2000) Personal Communication. John Sweeten, Texas A&M University and Indra Mitra, ERG. June 2000.

UEP (1999) Voluntary Survey Results—Estimated Percentage Participation/Activity. Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

USDA (2023a) Quick Stats: Agricultural Statistics Database. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: http://quickstats.nass.usda.gov/.

USDA (2023b) Chicken and Eggs 2022 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2023. Available online at: https://www.nass.usda.gov/Publications/.

USDA (2023c) Poultry - Production and Value 2022 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2023. Available online at: https://www.nass.usda.gov/Publications/.

USDA (2021a) Chicken and Eggs 2020 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2021. Available online at: http://www.nass.usda.gov/Publications/index.asp.

USDA (2021b) Poultry - Production and Value 2020 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2021. Available online at: http://www.nass.usda.gov/Publications/index.asp.

USDA (2019a) Chicken and Eggs 2018 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019b) Poultry - Production and Value 2018 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019c) Chicken and Eggs 2013-2017 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. June 2019. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2019d) 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: https://www.nass.usda.gov/AgCensus/index.php. May 2019.

USDA (2018) Poultry - Production and Value 2017 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2018. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2017) Poultry - Production and Value 2016 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2017. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2016) Poultry - Production and Value 2015 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2016. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2015) Poultry - Production and Value 2014 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2015. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2014) Poultry - Production and Value 2013 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2014. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2013a) Chicken and Eggs 2012 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2013. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2013b) Poultry - Production and Value 2012 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2013. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2012a) Chicken and Eggs 2011 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2012. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2012b) Poultry - Production and Value 2011 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2012. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2011a) Chicken and Eggs 2010 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2011. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2011b) Poultry - Production and Value 2010 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2011. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2010a) Chicken and Eggs 2009 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2010. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2010b) Poultry - Production and Value 2009 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2010. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009a) Chicken and Eggs 2008 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2009. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009b) Poultry - Production and Value 2008 Summary. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2009. Available online at: http://www.nass.usda.gov/Publications/index.php.

USDA (2009c) Chicken and Eggs – Final Estimates 2003-2007. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 2009. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2009d) Poultry Production and Value—Final Estimates 2003-2007. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. May 2009. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2008) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture.

USDA (2004a) Chicken and Eggs—Final Estimates 1998-2003. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (2004b) Poultry Production and Value—Final Estimates 1998-2002. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1999) Poultry Production and Value—Final Estimates 1994-97. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1999. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1998) Chicken and Eggs—Final Estimates 1994-97. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1998. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1996) Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH), Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1995a) Poultry Production and Value—Final Estimates 1988-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1995. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1995b) Chicken and Eggs—Final Estimates 1988-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1995. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA (1994) Sheep and Goats—Final Estimates 1989-1993. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. January 31, 1994. Available online at: https://www.nass.usda.gov/Publications/index.php.

USDA APHIS (2003) Sheep 2001, Part I: Reference of Sheep Management in the United States, 2001 and Part IV: Baseline Reference of 2001 Sheep Feedlot Health and Management. USDA-APHIS-VS. Fort Collins, CO. #N356.0702. Available online at http://www.aphis.usda.gov/animal_health/nahms/sheep/index.shtml#sheep2001.

USDA APHIS (2000) Layers '99—Part II: References of 1999 Table Egg Layer Management in the U.S. USDA-APHIS-VS. Fort Collins, CO. Available online at http://www.aphis.usda.gov/animal_health/nahms/poultry/downloads/layers99/Layers99_dr_PartII.pdf.

USDA APHIS (1996) Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices. USDA-APHIS-VS. Fort Collins, CO. Available online at: http://www.aphis.usda.gov/animal_health/nahms/swine/downloads/swine95/Swine95_dr_PartII.pdf.

Rice Cultivation

Baicich, P. (2013) The Birds and Rice Connection. *Bird Watcher's Digest*. Available online at: http://www.usarice.com/doclib/194/6867.pdf.

Brockwell, P.J., and R.A. Davis (2016) Introduction to time series and forecasting. Springer.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Cheng, K., S.M. Ogle, W.J. Parton, G. Pan. (2014) "Simulating greenhouse gas mitigation potentials for Chinese croplands using the DAYCENT ecosystem model." *Global Change Biology* 20:948-962.

Cheng, K., S.M. Ogle, W.J. Parton and G. Pan. (2013) "Predicting methanogenesis from rice paddies using the DAYCENT ecosystem model." *Ecological Modelling* 261-262:19-31.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." Global Biogeochemical Cycles, 24, GB1009, doi:10.1029/2009GB003544.

Deren, C. (2002) Personal Communication and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

Fitzgerald, G.J., K. M. Scow & J. E. Hill (2000) "Fallow Season Straw and Rice Management Effects on Methane Emissions in California Rice." Global biogeochemical cycles, 14 (3), 767-776.

Fleskes, J.P., Perry, W.M., Petrik, K.L., Spell, R., and Reid, F. (2005) Change in area of winter-flood and dry rice in the northern Central Valley of California determined by satellite imagery. California Fish and Game, 91: 207-215.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Hardke, J.T. (2015) Trends in Arkansas rice production, 2014. B.R. Wells Arkansas Rice Research Studies 2014. Norman, R.J. and Moldenhauer, K.A.K. (Eds.). Research Series 626, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J. (2014) Personal Communication. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Kirsten Jaglo, ICF International. September 11, 2014.

Hardke, J. (2013) Email correspondence. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Cassandra Snow, ICF International. July 15, 2013.

Hardke, J.T., and Wilson, C.E. Jr., (2014) Trends in Arkansas rice production, 2013. B.R. Wells Arkansas Rice Research Studies 2013. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 617, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J.T., and Wilson, C.E. Jr., (2013) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2012. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 609, Arkansas Agricultural Experiment Station, University of Arkansas.

Hollier, C. A. (ed), (1999) Louisiana rice production handbook. Louisiana State University Agricultural Center. LCES Publication Number 2321. 116 pp.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler (1985) "Production, Oxidation, and Emissions of Methane in Rice Paddies." *FEMS Microbiology Ecology,* 31:343-351.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D.M., and R. Mueller (2010) The 2009 Cropland Data Layer. Photogrammetric engineering and remote sensing 76:1201-1205.

Kirstein, A. (2003 through 2004, 2006) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL and ICF International.

Klosterboer, A. (1997, 1999 through 2003) Personal Communication. Arlen Klosterboer, retired Extension Agronomist, Texas A&M University and ICF International. July 7, 2003.

Lindau, C.W. and P.K. Bollich (1993) "Methane Emissions from Louisiana First and Ratoon Crop Rice." *Soil Science,* 156:42-48.

Linquist, B.A., M.A. Adviento-Borbe, C.M. Pittelkow, C.v. Kessel, et al. (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research*, 135:10-21.

Linscombe, S. (1999, 2001 through 2014) Email correspondence. Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center and ICF International.

LSU, (2015) Louisiana ratoon crop and conservation: Ratoon & Conservation Tillage Estimates. Louisiana State University, College of Agriculture AgCenter. Online at: www.lsuagcenter.com.

Miller, M.R., Garr, J.D., and Coates, P.S., (2010) Changes in the status of harvested rice fields in the Sacramento Valley, California: Implications for wintering waterfowl. Wetlands, 30: 939-947.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Neue, H.U., R. Wassmann, H.K. Kludze, W. Bujun, and R.S. Lantin (1997) "Factors and processes controlling methane emissions from rice fields." *Nutrient Cycling in Agroecosystems* 49: 111-117.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. (2007) "An empirically based approach for estimating uncertainty associated with modeling carbon sequestration in soils." *Ecological Modelling* 205:453-463.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., S. Spencer, M. Hartman, L. Buendia, L. Stevens, D. du Toit, J. Witi (2016) "Developing national baseline GHG emissions and analyzing mitigation potentials for agriculture and forestry using an advanced national GHG inventory software system." In Advances in Agricultural Systems Modeling 6, *Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forestry Systems to Guide Mitigation and Adaptation*, S. Del Grosso, L.R. Ahuja and W.J. Parton (eds.), American Society of Agriculture, Crop Society of America and Soil Science Society of America, pp. 129-148.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". Glob. Planet. Chang. 19: 35-48.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." Soil Science Society of America Journal 51:1173-1179.

Särndal C-E, Swensson B, Wretman, J (1992) Model Assisted Survey Sampling. Springer, New York.

Sass, R. L. (2001) CH_4 Emissions from Rice Agriculture. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. 399-417. Available online at: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_7_CH4_Rice_Agriculture.pdf.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner (1990) "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles,* 4:47-68.

Sass, R.L., F.M. Fisher, S.T. Lewis, M.F. Jund, and F.T. Turner. (1994) "Methane emissions from rice fields: effect of soil texture." *Global Biogeochemical Cycles* 8:135-140.

Schueneman, T. (1997, 1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International.

Slaton, N. (1999 through 2001) Personal Communication. Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service and ICF International.

Stansel, J. (2004 through 2005) Email correspondence. Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center and ICF International.

TAMU (2015) Texas Rice Crop Survey. Texas A&M AgriLIFE Research Center at Beaumont. Online at: https://beaumont.tamu.edu/.

Texas Agricultural Experiment Station (2007 through 2014) *Texas Rice Acreage by Variety*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System. Available online at: http://beaumont.tamu.edu/CropSurvey/CropSurveyReport.aspx.

Texas Agricultural Experiment Station (2006) *2005 - Texas Rice Crop Statistics Report*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System, p. 8. Available online at: http://beaumont.tamu.edu/eLibrary/TRRFReport_default.htm.

University of California Cooperative Extension (UCCE) (2015) Rice Production Manual. Revised (2015) UCCE, Davis, in collaboration with the California Rice Research Board.

USDA (2005 through 2015) *Crop Production Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu.

USDA (2012) *Summary of USDA-ARS Research on the Interrelationship of Genetic and Cultural Management Factors That Impact Grain Arsenic Accumulation in Rice*. News and Events. Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://www.ars.usda.gov/is/pr/2012/120919.htm. September 2013.

USDA (2003) *Field Crops, Final Estimates 1997-2002*. Statistical Bulletin No. 982. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/usda/reports/general/sb/. September 2005.

USDA (1998) *Field Crops Final Estimates 1992-1997*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/. July 2001.

USDA (1994) *Field Crops Final Estimates 1987-1992*. Statistical Bulletin Number 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/. July 2001.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

van Bodegom, P.M., R. Wassmann, T.M. Metra-Corton (2001) "A process based model for methane emission predictions from flooded rice paddies." *Global Biogeochemical Cycles* 15: 247-263.

Wang, J.J., S.K. Dodla, S. Viator, M. Kongchum, S. Harrison, S. D. Mudi, S. Liu, Z. Tian (2013) Agriculture Field Management Practices and Greenhouse Gas Emissions from Louisiana Soils. *Louisiana Agriculture*, Spring 2013: 8-9. Available online at: http://www.lsuagcenter.com/NR/rdonlyres/78D8B61A-96A8-49E1-B2EF-BA1D4CE4E698/93016/v56no2Spring2013.pdf.

Wassmann, R. H.U. Neue, R.S. Lantin, K. Makarim, N. Chareonsil5, L.V. Buendia, and H. Rennenberg (2000a) Characterization of methane emissions from rice fields in Asia II. Differences among irrigated, rainfed, and deepwater rice." *Nutrient Cycling in Agroecosystems*, 58(1):13-22.

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, et al. (2000b) "Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs." *Nutrient Cycling in Agroecosystems*, 58(1):23-36.

Way, M.O., McCauley, G.M., Zhou, X.G., Wilson, L.T., and Morace, B. (Eds.), (2014) 2014 Texas Rice Production Guidelines. Texas A&M AgriLIFE Research Center at Beaumont.

Wilson, C. (2002 through 2007, 2009 through 2012) Personal Communication. Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service and ICF International.

Wilson, C.E. Jr., and Branson, J.W., (2006) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2005. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 540, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Branson, J.W., (2005) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2004. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 529, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., and Mazzanti, R., (2010) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2009. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 581, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., Runsick, S.K., Mazzanti, R., (2009) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies (2008) Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 571, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K., (2008) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2007. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 560, Arkansas Agricultural Experiment Station, University of Arkansas.

Wilson, C.E. Jr., and Runsick, S.K., (2007) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2006. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 550, Arkansas Agricultural Experiment Station, University of Arkansas.

Yan, X., H. Akiyana, K. Yagi, and H. Akimoto (2009) “Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines.” *Global Biogeochemical Cycles*, 23, DOI: 0.1029/2008GB003299.

Yang, L., et al. (2018). "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies.” ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Young, M. (2013) Rice and Ducks. Ducks Unlimited, Memphis, TN. Available online at: http://www.ducks.org/conservation/farm-bill/rice-and-ducks---by-matt-young.

Agricultural Soil Management

AAPFCO (2008 through 2022) Commercial Fertilizers: 2008-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers: 1995-2007. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

Cheng, B., and D.M. Titterington (1994) "Neural networks: A review from a statistical perspective." Statistical science 9: 2-30.

Claassen, R., M. Bowman, J. McFadden, D. Smith, and S. Wallander (2018) Tillage intensity and conservation cropping in the United States, EIB 197. United States Department of Agriculture, Economic Research Service, Washington, D.C.

CTIC (2004) 2004 Crop Residue Management Survey. Conservation Technology Information Center. Available at http://www.ctic.purdue.edu/CRM/.

Del Grosso, S. J., S. M. Ogle, C. Nevison, R. Gurung, W. J. Parton, C. Wagner-Riddle, W. Smith, W. Winiwarter, B. Grant, M. Tenuta, E. Marx, S. Spencer, and S. Williams. 2022. A gap in nitrous oxide emission reporting complicates long-term climate mitigation. Proceedings of the National Academy of Sciences 119:e2200354119.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research*, 83: 9-24. doi: 10.1016/j.still.2005.02.007.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544.

Del Grosso, S.J., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating agricultural nitrous oxide emissions. EOS 89, 529-530.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.). Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press. Boca Raton, Florida. 303-332.

Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DAYCENT modeling package and additional procedures for parameterization, calibration, validation, and applications, in Methods of Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA.

Delgado, J.A., S.J. Del Grosso, and S.M. Ogle (2009) "15N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated." *Nutrient Cycling in Agroecosystems*, DOI 10.1007/s10705-009-9300-9.

Edmonds, L., N. Gollehon, R.L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaeffer (2003) "Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans." Part 1. Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping. Natural Resource Conservation Service, U.S. Department of Agriculture.

EPA (2003) Clean Watersheds Needs Survey 2000—Report to Congress, U.S. Environmental Protection Agency. Washington, D.C. Available online at: http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: http://biosolids.policy.net/relatives/18941.PDF.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403, and 503.

Firestone, M. K., and E.A. Davidson, Ed. (1989) Microbiological basis of NO and N_2O production and consumption in soil. Exchange of trace gases between terrestrial ecosystems and the atmosphere. New York, John Wiley & Sons.

Friedman, J.H. (2001) "Greedy function approximation: A gradient boosting machine." Ann. Statist. 29 (5) 1189 – 1232.

Hagen, S. C., G. Delgado, P. Ingraham, I. Cooke, R. Emery, J. P. Fisk, L. Melendy, T. Olson, S. Patti, N. Rubin, B. Ziniti, H. Chen, W. Salas, P. Elias, and D. Gustafson. 2020. Mapping Conservation Management Practices and Outcomes in the Corn Belt Using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. Land **9**:408.

ILENR (1993) Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990. Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. The Intergovernmental Panel on Climate Change. [T, Hiraishi, T. Krug, K. Tanabe, N. Srivastava, B. Jamsranjav, M. Fukuda and T. Troxler (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M.

Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D.M., and R. Mueller (2010) The 2009 Cropland Data Layer. Photogrammetric engineering and remote sensing 76:1201-1205.

Little, R. (1988) "Missing-data adjustments in large surveys." *Journal of Business and Economic Statistics* 6: 287–296.

McFarland, M.J. (2001) Biosolids Engineering, New York: McGraw-Hill, p. 2.12.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mosier A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput (1998) Closing the global atmospheric N_2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle, Nutrient Cycling in Agroecosystems, 52, 225-248.

NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association, July 21, 2007.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Noller, J. (1996) Personal Communication. John Noller, Missouri Department of Natural Resources and Heike Mainhardt, ICF Incorporated. July 30, 1996.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." Global Change Biology 16:810-822.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205:453-463.

Oregon Department of Energy (1995) Report on Reducing Oregon's Greenhouse Gas Emissions: Appendix D Inventory and Technical Discussion. Oregon Department of Energy. Salem, OR.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing." *Glob. Planet. Chang*. 19: 35-48.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Pukelsheim, F. (1994) “The 3-Sigma-Rule.” American Statistician 48:88-91.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001. Scientific Investigations Report 2006-5012. U.S Department of the Interior.

Särndal C-E, Swensson B, Wretman, J (1992) Model Assisted Survey Sampling. Springer, New York.

Scheer, C., S.J. Del Grosso, W.J. Parton, D.W. Rowlings, P.R. Grace (2013) Modeling Nitrous Oxide Emissions from Irrigated Agriculture: Testing DAYCENT with High Frequency Measurements, Ecological Applications, in press. Available online at: http://dx.doi.org/10.1890/13-0570.1.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

TVA (1991 through 1992a, 1993 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

USDA-ERS (2020) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: http://www.ers.usda.gov/data/archive/93018/.

USDA-NASS (2023) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C., Accessed August 2023, http://quickstats.nass.usda.gov/.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2017) 2017 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2012) 2012 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH.

USDA-NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf.

USDA-NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH.

USDA-NRCS (2022) Conversation practice on cultivated croplands: A comparison of CEAP I and CEAP II survey data and modeling. United States Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/sites/default/files/2022-09/CEAP-Croplands-ConservationPracticesonCultivatedCroplands-Report-March2022.pdf.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. U.S. Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

USFS (2019) Forest Inventory and Analysis Program. United States Department of Agriculture, U.S. Forest Service, https://www.fia.fs.fed.us/tools-data/default.asp.

Van Buuren, S. (2012) "Flexible imputation of missing data." Chapman & Hall/CRC, Boca Raton, FL.

Wagner-Riddle, C., Congreves, K. A., Abalos, D., Berg, A. A., Brown, S. E., Ambadan, J. T., Gao, X. & Tenuta, M. (2017) "Globally important nitrous oxide emissions from croplands induced by freeze-thaw cycles." *Nature Geosciences* 10(4): 279-283.

Wisconsin Department of Natural Resources (1993) Wisconsin Greenhouse Gas Emissions: Estimates for 1990. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Liming

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Tepordei, V.V. (1994 through 2015) "Crushed Stone," In Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. Available online at: http://minerals.usgs.gov/minerals/.

Tepordei, V.V. (2003b) Personal communication. Valentin Tepordei, U.S. Geological Survey and ICF Consulting, August 18, 2003.

USGS (2023) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2023, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2022) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2022, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2021) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2021, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

USGS (2020) Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2020, U.S. Geological Survey, Reston, VA. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis.

West, T.O., and A.C. McBride (2005) "The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions," Agricultural Ecosystems & Environment 108:145-154.

West, T.O. (2008) Email correspondence. Tristram West, Environmental Sciences Division, Oak Ridge National Laboratory, U.S. Department of Energy and Nikhil Nadkarni, ICF International on suitability of liming emission factor for the entire United States. June 9, 2008.

Willett, J.C. (2023a) "Crushed Stone," In Minerals Yearbook 2021. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed November 2023

Willett, J.C. (2023b) Personal communication. Jason Willett. Preliminary data tables from "Crushed Stone," In 2022 Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. November, 2023.

Willett, J.C. (2022a) "Crushed Stone," In Minerals Yearbook 2018. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022.

Willett, J.C. (2022b) "Crushed Stone," In Minerals Yearbook 2019. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022

Willett, J.C. (2022c) "Crushed Stone," In Minerals Yearbook 2020. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information. Accessed October 2022

Willett, J.C. (2022d) Personal communication. Jason Willett. Preliminary data tables from "Crushed Stone," In 2021 Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. October, 2022.

Willett, J.C. (2020a) "Crushed Stone," In Minerals Yearbook 2016. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis. Accessed November 2020.

Urea Fertilization

AAPFCO (2008 through 2022) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

AAPFCO (2000b) 1999-2000 Commercial Fertilizers Data, ASCII files. Available from David Terry, Secretary, AAPFCO.

EPA (2000) Preliminary Data Summary: Airport Deicing Operations (Revised). EPA-821-R-00-016. August 2000.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Itle, C. (2009) Email correspondence. Cortney Itle, ERG and Tom Wirth, U.S. Environmental Protection Agency on the amount of urea used in aircraft deicing. January 7, 2009.

TVA (1991 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) Fertilizer Summary Data 1992. Tennessee Valley Authority, Muscle Shoals, AL.

Field Burning of Agricultural Residues

Akintoye, H.A., Agbeyi, E.O., and Olaniyan, A.B. (2005) “The effects of live mulches on tomato (Lycopersicon esculentum) yield under tropical conditions.” *Journal of Sustainable Agriculture* 26: 27-37.

Bange, M.P., Milroy, S.P., and Thongbai, P. (2004) “Growth and yield of cotton in response to waterlogging.” *Field Crops Research* 88: 129-142.

Beyaert, R.P. (1996) *The effect of cropping and tillage management on the dynamics of soil organic matter*. PhD Thesis. University of Guelph.

Bouquet, D.J., and Breitenbeck, G.A. (2000) “Nitrogen rate effect on partitioning of nitrogen and dry matter by cotton.” *Crop Science* 40: 1685-1693.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer. Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Brouder, S.M., and Cassman, K.G (1990) “Root development of two cotton cultivars in relation to potassium uptake and plant growth in a vermiculitic soil.” *Field Crops Res.* 23: 187-203.

Costa, L.D., and Gianquinto, G. (2002) “Water stress and watertable depth influence yield, water use efficiency, and nitrogen recovery in bell pepper: lysimeter studies.” *Aust. J. Agric. Res.* 53: 201–210.

Crafts-Brandner, S.J., Collins, M., Sutton, T.G., and Burton, H.R. (1994) “Effect of leaf maleic hydrazide concentration on yield and dry matter partitioning in burley tobacco (Nicotiana tabacum L.).” *Field Crops Research* 37: 121-128.

De Pinheiro Henriques, A.R., and Marcelis, L.F.M. (2000) “Regulation of growth at steady-state nitrogen nutrition in lettuce (Lactuca sativa L.): Interactive effects of nitrogen and irradiance.” *Annals of Botany* 86: 1073-1080.0.

Díaz-Pérez, J.C., Silvoy, J., Phatak,S.C., Ruberson, J., and Morse, R. (2008) Effect of winter cover crops and co-till on the yield of organically-grown bell pepper (Capsicum annum L.). *Acta Hort*. 767:243-247.

Dua, K.L., and Sharma, V.K. (1976) “Dry matter production and energy contents of ten varieties of sugarcane at Muzaffarnagar (Western Uttar Pradesh).” *Tropical Ecology* 17: 45-49.

Fritschi, F.B., Roberts, B.A., Travis, R.L., Rains, D.W., and Hutmacher, R.B. (2003) “Seasonal nitrogen concentration, uptake, and partitioning pattern of irrigated Acala and Pima cotton as influenced by nitrogen fertility level.” *Crop Science* 44:516–527.

Gerik, T.J., K.L. Faver, P.M. Thaxton, and K.M. El-Zik. (1996) “Late season water stress in cotton: I. Plant growth, water use, and yield.” *Crop Science* 36: 914–921.

Gibberd, M.R., McKay, A.G., Calder, T.C., and Turner, N.C. (2003) “Limitations to carrot (Daucus carota L.) productivity when grown with reduced rates of frequent irrigation on a free-draining, sandy soil.” *Australian Journal of Agricultural Research* 54: 499-506.

Giglio, L., I. Csiszar, and C.O. Justice (2006) “Global distribution and seasonality of active fires as observed with the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors” J. Geophys. Res. 111, G02016, doi:10.1029/2005JG000142.

Giglio, L., Justice, C., Boschetti, L., Roy, D. (2015) “*MCD64A1 MODIS/Terra+Aqua Burned Area Monthly L3 Global 500m SIN Grid V006* [Data set]”. NASA EOSDIS Land Processes Distributed Active Archive Center. Accessed 2023-12-05 from https://doi.org/10.5067/MODIS/MCD64A1.006.

Halevy, J. (1976) “Growth rate and nutrient uptake of two cotton cultivars grown under irrigation.” *Agronomy Journal* 68: 701-705.

Halvorson, A.D., Follett, R.F., Bartolo, M.E., and Schweissing, F.C. (2002) “Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn.” *Agronomy Journal* 94: 442-449.

Heitholt, J.J., Pettigrew, W.T., and Meredith, W.R. (1992) “Light interception and lint yield of narrow-row cotton.” *Crop Science* 32: 728-733.

Hollifield, C.D., Silvertooth, J.C., and Moser, H. (2000) "Comparison of obsolete and modern cotton cultivars for irrigated production in Arizona." *2000 Arizona Cotton Report*, University of Arizona College of Agriculture, http://ag.arizona.edu/pubs/crops/az1170/.

Hopkinson, J.M. (1967) "Effects of night temperature on the growth of Nicotiana tabacum." *Australian Journal of Experimental Agriculture and Animal Husbandry* 7: 78–82.

Huett, D.O., and Dettman, E.B. (1991) Effect of nitrogen on growth, quality and nutrient uptake of cabbages grown in sand culture. *Australian Journal of Experimental Agriculture* 29: 875-81.

Huett, D.O., and Dettman, B. (1989) "Nitrogen response surface models of zucchini squash, head lettuce and potato." *Plant and Soil* 134: 243-254.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Jacobs, J.L., Ward, G.N., and Kearney, G. (2004) "Effects of irrigation strategies and nitrogen fertilizer on turnip dry matter yield, water use efficiency, nutritive characteristics and mineral content in western Victoria." *Australian Journal of Experimental Agriculture* 44: 13-26.

Jacobs, J.L., Ward, G.N., McDowell, A.M., and Kearney, G. (2002) "Effect of seedbed cultivation techniques, variety, soil type and sowing time, on brassica dry matter yields, water use efficiency and crop nutritive characteristics in western Victoria." *Australian Journal of Experimental Agriculture* 42: 945-952.

Jacobs, J.L., Ward, G.N., McDowell, A.M., and Kearney, G.A. (2001) "A survey on the effect of establishment techniques, crop management, moisture availability and soil type on turnip dry matter yields and nutritive characteristics in western Victoria." *Australian Journal of Experimental Agriculture* 41: 743–751.

Kage, H., Alt, C., and Stűtzel, H. (2003) "Aspects of nitrogen use efficiency of cauliflower II. Productivity and nitrogen partitioning as influenced by N supply." *Journal of Agricultural Science* 141: 17–29.

Kumar, A., Singh, D.P., and Singh, P. (1994) "Influence of water stress on photosynthesis, transpiration, water-use efficiency and yield of Brassica juncea L." *Field Crops Research* 37: 95-101.

LANDFIRE (2008) Existing Vegetation Type Layer, LANDFIRE 1.1.0, U.S. Department of the Interior, Geological Survey. Accessed 28 October 2010 at http://landfire.cr.usgs.gov/viewer/.

MacLeod, L.B., Gupta, U.C., and Cutcliffe, J.A. (1971) "Effect of N, P, and K on root yield and nutrient levels in the leaves and roots of rutabagas grown in a greenhouse." *Plant and Soil* 35: 281-288.

Mahrani, A., and Aharonov, B. (1964) "Rate of nitrogen absorption and dry matter production by upland cotton grown under irrigation." *Israel J. Agric. Res.* 14: 3-9.

Marcussi, F.F.N., Bôas, R.L.V., de Godoy, L.J.G., and Goto, R. (2004) "Macronutrient accumulation and partitioning in fertigated sweet pepper plants." *Sci. Agric. (Piracicaba, Braz.)* 61: 62-68.

McCarty, J.L. (2011) "Remote Sensing-Based Estimates of Annual and Seasonal Emissions from Crop Residue Burning in the Contiguous United States." *Journal of the Air & Waste Management Association*, 61:1, 22-34, DOI: 10.3155/1047-3289.61.1.22.

McCarty, J.L. (2010) Agricultural Residue Burning in the Contiguous United States by Crop Type and State. Geographic Information Systems (GIS) Data provided to the EPA Climate Change Division by George Pouliot, Atmospheric Modeling and Analysis Division, EPA. Dr. McCarty's research was supported by the NRI Air Quality Program of the Cooperative State Research, Education, and Extension Service, USDA, under Agreement No. 20063511216669 and the NASA Earth System Science Fellowship.

McCarty, J.L. (2009) *Seasonal and Interannual Variability of Emissions from Crop Residue Burning in the Contiguous United States*. Dissertation. University of Maryland, College Park.

McPharlin, I.R., Aylmore, P.M., and Jeffery, R.C. (1992) "Response of carrots (Daucus carota L.) to applied phosphorus and phosphorus leaching on a Karrakatta sand, under two irrigation regimes." *Australian Journal of Experimental Agriculture* 32:225-232.

Mondino, M.H., Peterlin, O.A., and Garay, F. (2004) "Response of late-planted cotton to the application of growth regulator (chlorocholine chloride, CYCOCEL 75)." *Expl Agric.* 40: 381–387.

Moustakas, N.K., and Ntzanis, H. (2005) "Dry matter accumulation and nutrient uptake in flue-cured tobacco (Nicotiana tabacum L.)." *Field Crops Research* 94: 1-13.

Peach, L., Benjamin, L.R., and Mead, A. (2000) "Effects on the growth of carrots (Daucus carota L.), cabbage (Brassica oleracea var. capitata L.) and onion (Allium cepa L.) of restricting the ability of the plants to intercept resources." *Journal of Experimental Botany* 51: 605-615.

Pettigrew, W.T., and Meredith, W.R., Jr. (1997) "Dry matter production, nutrient uptake, and growth of cotton as affected by potassium fertilization." *J. Plant Nutr.* 20:531–548.

Pettigrew, W.T., Meredith, W.R., Jr., and Young, L.D. (2005) "Potassium fertilization effects on cotton lint yield, yield components, and reniform nematode populations." *Agronomy Journal* 97: 1245-1251.

PRISM Climate Group (2015) PRISM Climate Data. Oregon State University. July 24, 2015. Available online at: http://prism.oregonstate.edu.

Reid, J.B., and English, J.M. (2000) "Potential yield in carrots (Daucus carota L.): Theory, test, and an application." *Annals of Botany* 85: 593-605.

Sadras, V.O., and Wilson, L.J. (1997) "Growth analysis of cotton crops infested with spider mites: II. Partitioning of dry matter." *Crop Science* 37: 492-497.

Scholberg, J., McNeal, B.L., Jones, J.W., Boote, K.J., Stanley, C.D., and Obreza, T.A. (2000a) "Growth and canopy characteristics of field-grown tomato." *Agronomy Journal* 92: 152-159.

Scholberg, J., McNeal, B.L., Boote, K.J., Jones, J.W., Locasio, S.J., and Olson, S.M. (2000b) "Nitrogen stress effects on growth and nitrogen accumulation by field-grown tomato." *Agronomy Journal* 92:159-167.

Singels, A. and Bezuidenhout, C.N. (2002) "A new method of simulating dry matter partitioning in the Canegro sugarcane model." *Field Crops Research* 78: 151 - 164.

Sitompul, S.M., Hairiah, K., Cadisch, G., and Van Noordwuk, M. (2000) "Dynamics of density fractions of macro-organic matter after forest conversion to sugarcane and woodlots, accounted for in a modified Century model." *Netherlands Journal of Agricultural Science* 48: 61-73.

Stirling, G.R., Blair, B.L., Whittle, P.J.L., and Garside, A.L. (1999) "Lesion nematode (Pratylenchus zeae) is a component of the yield decline complex of sugarcane." In: Magarey, R.C. (Ed.), *Proceedings of the First Australasian Soilborne Disease Symposium*. Bureau of Sugar Experiment Stations, Brisbane, pp. 15–16.

Tan, D.K.Y., Wearing, A.H., Rickert, K.G., and Birch, C.J. (1999) "Broccoli yield and quality can be determined by cultivar and temperature but not photoperiod in south-east Queensland." *Australian Journal of Experimental Agriculture* 39: 901–909.

Tadesse, T., Nichols, M.A., and Fisher, K.J. (1999) Nutrient conductivity effects on sweet pepper plants grown using a nutrient film technique. 1. Yield and fruit quality. New Zealand Journal of Crop and Horticultural Science, 27: 229-237.

Torbert, H.A., and Reeves, D.W. (1994) "Fertilizer nitrogen requirements for cotton production as affected by tillage and traffic." Soil Sci. Soc. Am. J. 58:1416-1423.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2019) Quick Stats: U.S. & All States Data; Crops; Production and Area Harvested; 1990 - 2018. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, D.C. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at: http://quickstats.nass.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Valantin, M., Gary, C., Vaissiére, B.E., and Frossard, J.S. (1999) "Effect of fruit load on partitioning of dry matter and energy in cantaloupe (Cucumis melo L.)." *Annals of Botany* 84: 173-181.

Wallach, D., Marani, A., and Kletter, E. (1978) "The relation of cotton crop growth and development to final yield." *Field Crops Research* 1: 283-294.

Wells, R., and Meredith, W.R., Jr. (1984) "Comparative growth of obsolete and modern cultivars. I. Vegetative dry matter partitioning." *Crop Science* 24: 858-872.4.

Wiedenfels, R.P. (2000) "Effects of irrigation and N fertilizer application on sugarcane yield and quality." *Field Crops Research* 43: 101-108.

Land Use, Land-Use Change, and Forestry

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Representation of the U.S. Land Base

Alaska Department of Natural Resources (2006) Alaska Infrastructure 1:63,360. Available online at: http://dnr.alaska.gov/SpatialUtility/SUC?cmd=extract&layerid=75.

Alaska Interagency Fire Management Council (1998) Alaska Interagency Wildland Fire Management Plan. Available online at: http://agdc.usgs.gov/data/blm/fire/index.html.

Alaska Oil and Gas Conservation Commission (2009) Oil and Gas Information System. Available online at: http://doa.alaska.gov/ogc/publicdb.html.

Dewitz, J., 2023, National Land Cover Database (NLCD) 2021 Products: U.S. Geological Survey data release, https://doi.org/10.5066/P9JZ7AO3.

EIA (2011) Coal Production and Preparation Report Shapefile. Available online at: http://www.eia.gov/state/notes-sources.cfm#maps.

ESRI (2008) ESRI Data & Maps. Redlands, CA: Environmental Systems Research Institute. [CD-ROM].

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States, Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2010) Revisiting the use of managed land as a proxy for estimating national anthropogenic emissions and removals. [Eggleston HS, Srivastava N, Tanabe K, Baasansuren J, (eds.)]. Institute for Global Environmental Studies, Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. (2013) A comprehensive change detection method for updating the National Land Cover Database to circa 2011. Remote Sensing of Environment, 132: 159-175.

Nelson, M.D., Riitters, K.H., Coulston, J.W., Domke, G.M., Greenfield, E.J., Langner, L.L., Nowak, D.J., O'Dea, C.B., Oswalt, S.N., Reeves, M.C. and Wear, D.N. (2020) Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191., 191, pp.1-70.

NOAA Coastal Change Analysis Program (C-CAP) Regional Land Cover Database. Data collected 1995-present Charleston, SC: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center. Data accessed at: www.csc.noaa.gov/landcover.

Nusser, S.M. and J.J. Goebel (1997) "The national resources inventory: a long-term multi-resource monitoring programme." Environmental and Ecological Statistics 4:181-204.

Ogle, S.M., G. Domke, W.A. Kurz, M.T. Rocha, T. Huffman, A. Swan, J.E. Smith, C. Woodall, T. Krug (2018) Delineating managed land for reporting greenhouse gas emissions and removals to the United Nations Framework Convention on Climate Change. Carbon Balance and Management 13:9.

U.S. Census Bureau (2010) Topologically Integrated Geographic Encoding and Referencing (TIGER) system shapefiles. U.S. Census Bureau, Washington, D.C. Available online at: http://www.census.gov/geo/www/tiger.

U.S. Department of Agriculture (2015) County Data - Livestock, 1990-2014. U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, D.C.

U.S. Department of Agriculture, Forest Service. (2023) Timber Product Output (TPO) Reports. https://www.fia.fs.usda.gov/program-features/tpo/

U.S. Department of Interior (2005) Federal Lands of the United States. National Atlas of the United States, U.S. Department of the Interior, Washington D.C. Available online at: http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound.

United States Geological Survey (USGS), Gap Analysis Program (2012) Protected Areas Database of the United States (PADUS), version 1.3 Combined Feature Class. November 2012.

USGS (2012) Alaska Resource Data File. Available online at: http://ardf.wr.usgs.gov/.

USGS (2005) Active Mines and Mineral Processing Plants in the United States in 2003. U.S. Geological Survey, Reston, VA.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks

AF&PA (2006a and earlier) Statistical roundup. (Monthly). Washington, D.C. American Forest & Paper Association.

AF&PA (2006b and earlier) Statistics of paper, paperboard and wood pulp. Washington, D.C. American Forest & Paper Association.

AF&PA (2021) 2020 Statistics – Paper Industry – Annual Summary Data Through 2020. Washington, D.C.: American Forest and Paper Association, 54 p.

AF&PA (2023) Capacity & Fiber Consumption Survey – Paper Industry – 63rd Annual 2022-2023. Washington, D.C.: American Forest and Paper Association, 44 p.

Amichev, B.Y. and J.M. Galbraith (2004) "A Revised Methodology for Estimation of Forest Soil Carbon from Spatial Soils and Forest Inventory Data Sets." Environmental Management 33(Suppl. 1):S74-S86.

Bechtold, W.A.; Patterson, P.L. (2005) The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 85 p.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Coulston, J.W., Wear, D.N., and Vose, J.M. (2015) Complex forest dynamics indicate potential for slowing carbon accumulation in the southeastern United States. Scientific Reports. 5: 8002.

Deenik J, McClellan AT (2007) Soils of Hawai'i. Soil and Crop Management, SCM-20. College of Tropical Agriculture and Human Resources, University of Hawai'i at Manoa, Honolulu.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., Nave, L., Swanston, C. (2017) Toward inventory-based estimates of soil organic carbon in forests of the United States. Ecological Applications. 27(4), 1223-1235.

Domke, G.M., Walters, B.F., Smith, J.E., Woodall, C.W. (2022) Chapter 6: FIA Carbon Attributes. In Sampling and estimation documentation for the Enhanced Forest Inventory and Analysis Program: 2022. Westfall, J.A., Coulston, J.W., Moisen, G.G., Andersen, H.-E., eds. Gen. Tech. Rep. NRS-GTR-207, Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 129 p. https://doi.org/10.2737/NRS-GTR-207.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E. (2012) Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. Forest Ecology and Management. 270: 108-116.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

EPA (2006) Municipal solid waste in the United States: 2005 Facts and figures. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. (5306P) EPA530-R-06-011. Available online at: http://www.epa.gov/msw/msw99.htm.

FAO. Forestry Production and Trade. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/FO. Data of Access: 13-09-2023.

Frayer, W.E., and G.M. Furnival (1999) "Forest Survey Sampling Designs: A History." Journal of Forestry 97(12): 4-10.

Freed, R. (2004) Open-dump and Landfill timeline spreadsheet (unpublished). ICF International. Washington, D.C.

Hair, D. (1958) "Historical forestry statistics of the United States." Statistical Bull. 228. U.S. Department of Agriculture Forest Service, Washington, D.C.

Hair. D. and A.H. Ulrich (1963) The Demand and price situation for forest products – 1963. U.S. Department of Agriculture Forest Service, Misc Publication No. 953. Washington, D.C.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Howard, J. L. and Liang, S. (2019) U.S. timber production, trade, consumption, and price statistics 1965 to 2017. Res. Pap. FPL-RP-701. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. and Jones, K.C. (2016) U.S. timber production, trade, consumption, and price statistics 1965 to 2013. Res. Pap. FPL-RP-679. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. (2007) U.S. timber production, trade, consumption, and price statistics 1965 to 2005. Res. Pap. FPL-RP-637. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

Howard, J. L. (2003) U.S. timber production, trade, consumption, and price statistics 1965 to 2002. Res. Pap. FPL-RP-615. Madison, WI: USDA, Forest Service, Forest Products Laboratory. Available online at: http://www.fpl.fs.fed.us/documnts/fplrp/fplrp615/fplrp615.pdf.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T.G. (eds.)]. Switzerland.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., Harrison, R.B., Guerrini, I.A., deB Richter Jr., D., Rustad, L., Lorenz, K., Chabbi, A., Miglietta, F. (2014) Current status, uncertainty and future needs in soil organic carbon monitoring. Science of the Total Environment, 468, 376-383.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Johnson, K. Domke, G.M., Russell, M.B., Walters, B.F., Hom, J., Peduzzi, A., Birdsey, R., Dolan, K., Huang, W. (2017) Estimating aboveground live understory vegetation carbon in the United States. Environmental Research Letters.

Johnson, M.G. and Kern, J.S., (2002.) Quantifying the organic carbon held in forested soils of the United States and Puerto Rico. The potential of US forest soils to sequester and mitigate the greenhouse effect, Lewis, Boca Raton, pp.47-72.

Nelson, M.D., Riitters, K.H., Coulston, J.W., Domke, G.M., Greenfield, E.J., Langner, L.L., Nowak, D.J., O'Dea, C.B., Oswalt, S.N., Reeves, M.C. and Wear, D.N. (2020) Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191., 191, pp.1-70.

Ogle, S. M., G. M. Domke, W. A. Kurz, M. T. Rocha, T. Huffman, A. Swan, J. E. Smith, C. W. Woodall, and T. Krug. (2018) Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance and Management 13:9.

O'Neill, K.P., Amacher, M.C., Perry, C.H. (2005) Soils as an indicator of forest health: a guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis program. Gen. Tech. Rep. NC-258. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 53 p.

Oswalt, S.N., Brandeis, T.J. and Woodall, C.W., (2008). Contribution of dead wood to biomass and carbon stocks in the Caribbean: St. John, US Virgin Islands. Biotropica, 40(1), pp.20-27.

Oswalt, S.N., Smith, W.B., Miles, P.D. and Pugh, S.A. (2019) Forest resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office., 97.

Perry, C.H., C.W. Woodall, and M. Schoeneberger (2005) Inventorying trees in agricultural landscapes: towards an accounting of "working trees". In: "Moving Agroforestry into the Mainstream." Proc. 9th N. Am. Agroforestry Conf., Brooks, K.N. and Folliott, P.F. (eds.). 12-15 June 2005, Rochester, MN [CD-ROM]. Dept. of Forest Resources, Univ. Minnesota, St. Paul, MN, 12 p. Available online at: http://cinram.umn.edu/afta2005/. (verified 23 Sept 2006).

Russell, M.B.; D'Amato, A.W.; Schulz, B.K.; Woodall, C.W.; Domke, G.M.; Bradford, J.B. (2014) Quantifying understory vegetation in the U.S. Lake States: a proposed framework to inform regional forest carbon stocks. Forestry. 87: 629-638.

Russell, M.B.; Domke, G.M.; Woodall, C.W.; D'Amato, A.W. (2015) Comparisons of allometric and climate-derived estimates of tree coarse root carbon in forests of the United States. Carbon Balance and Management. 10: 20.

Selmants, P.C., Giardina, C.P., Jacobi, J.D., and Zhu, Zhiliang, eds. (2017) Baseline and projected future carbon storage and carbon fluxes in ecosystems of Hawai'i: U.S. Geological Survey Professional Paper 1834, 134 p., https://doi.org/10.3133/pp1834.

Skog, K.E. (2008) Sequestration of carbon in harvested wood products for the United States. Forest Products Journal 58:56-72.

Smith, J.E., Domke, G.M. and Woodall, C.W. (2022) Predicting downed woody material carbon stocks in forests of the conterminous United States. Science of the Total Environment, 803, p.150061.

Smith, J.E., L.S. Heath, and M.C. Nichols (2010) U.S. Forest Carbon Calculation Tool User's Guide: Forestland Carbon Stocks and Net Annual Stock Change. General Technical Report NRS-13 revised, U.S. Department of Agriculture Forest Service, Northern Research Station, 34 p.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Smith, W. B., P. D. Miles, C. H. Perry, and S. A. Pugh (2009) Forest Resources of the United States, 2007. General Technical Report WO-78, U.S. Department of Agriculture Forest Service, Washington Office.

Soil Survey Staff (2020a) Gridded National Soil Survey Geographic (gNATSGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service. Available online at https://nrcs.app.box.com/v/soils.

Soil Survey Staff (2020b) Gridded National Soil Survey Geographic (gNATSGO) Database for Alaska. United States Department of Agriculture, Natural Resources Conservation Service. Available online at https://nrcs.app.box.com/v/soils.

Steer, Henry B. (1948) Lumber production in the United States. Misc. Pub. 669, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1985) U.S. Timber Production, Trade, Consumption, and Price Statistics 1950-1985. Misc. Pub. 1453, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1989) U.S. Timber Production, Trade, Consumption, and Price Statistics, 1950-1987. USDA Miscellaneous Publication No. 1471, U.S. Department of Agriculture Forest Service. Washington, D.C., 77.

United Nations Framework Convention on Climate Change (UNFCC) (2013) Report on the individual review of the inventory submission of the United States of America submitted in 2012. FCCC/ARR/2012/USA. 42 p.

USDA Forest Service (2022a) PNW-FIA Hawai'i Inventory Database. Last accessed: 28 September 2023. https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-hawaii-inventory-database

USDA Forest Service (2022b) PNW-FIA Pacific Islands Inventory Database. Last accessed: 28 September 2023. https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-pacific-islands-database https://www.fs.usda.gov/research/pnw/products/dataandtools/tools/pnw-fia-hawaii-inventory-database

USDA Forest Service (2023a) Forest Inventory and Analysis National Program: Program Features. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/program-features/index.php. Accessed 28 September 2023.

USDA Forest Service. (2023b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 28 September 2023.

USDA Forest Service. (2023c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 28 September 2023.

USDA Forest Service (2023d) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at: https://www.fia.fs.usda.gov/library/database-documentation/index.php. Accessed on 28 September 2023.

U.S. Census Bureau (1976) Historical Statistics of the United States, Colonial Times to 1970, Vol. 1. Washington, D.C.

Wear, D.N., Coulston, J.W. (2015) From sink to source: Regional variation in U.S. forest carbon futures. Scientific Reports. 5: 16518.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. In press . A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104. Washington, DC: U.S. Department of Agriculture, Forest Service. 60 p. https//doi.org/10.2737/WO-GTR-104.

Westfall, J.A., Woodall, C.W., Hatfield, M.A. (2013) A statistical power analysis of woody carbon flux from forest inventory data. Climatic Change. 118: 919-931.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B., Will-Wolf, S. (2011b) "Status and future of the forest health indicators program of the United States." Environmental Monitoring and Assessment. 177: 419-436.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Anderson, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagan, S.C., Hanou, I.S.; Nichols, M.C., Perry, C.H., Russell, M.B., Westfall, J.A., Wilson, B.T. (2015a) The U.S. Forest Carbon Accounting Framework: Stocks and Stock change 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 pp.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Zhu, Zhiliang, and McGuire, A.D., eds. (2016) Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska: U.S. Geological Survey Professional Paper 1826, 196 p., Available online at: http://dx.doi.org/10.3133/pp1826.

Forest Land Remaining Forest Land: Non-CO_2 Emissions from Forest Fires

Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z.L., Quayle, B. and Howard, S. (2007) A project for monitoring trends in burn severity. Fire ecology, 3(1), pp.3-21.

French, N.H.F., W.J. de Groot, L.K. Jenkins, B.M. Rogers, E.C. Alvarado, B. Amiro, B. de Jong, S. Goetz, E. Hoy, E. Hyer, R. Keane, D. McKenzie, S.G. McNulty, B.E Law, R. Ottmar, D.R. Perez-Salicrup, J. Randerson, K.M. Robertson, and M. Turetsky (2011) "Model comparisons for estimating carbon emissions from North American wildland fire." Journal of Geophysical Research 116. 10.1029/2010JG001469

French, N.H.F., D. McKenzie, T. Erickson, B. Koziol, M. Billmire, K.A. Endsley, N.K.Y. Scheinerman, L. Jenkins, M.E. Miller, R. Ottmar, and S. Prichard (2014) "Modeling regional-scale fire emissions with the Wildland Fire Emissions Information System." Earth Interactions 18, no. 16

Giglio, L., Boschetti, L., Roy, D. P., Humber, M. L., and Justice, C. O. (2018) The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment, 217, 72-85.

IPCC (2019) Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Larkin, N. K., S. Raffuse, and T. T. Strand (2014) Wildland fire emissions, carbon, and climate: U.S. emissions inventories. For. Ecol. Manage. 317:61–69. doi:10.1016/j.foreco.2013.09.012.

MTBS Data Access: Fire Level Geospatial Data (August 2023) MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online at: http://mtbs.gov/direct-download. Accessed on 15 August 2023.

Ogle, S. M., G. M. Domke, W. A. Kurz, M. T. Rocha, T. Huffman, A. Swan, J. E. Smith, C. W. Woodall, and T. Krug. (2018) Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance and Management 13:9.

WFEIS (2023) Wildland Fire Emissions Inventory System, home page. https://wfeis.mtri.org/.

WFIGS (2023) WFIGS, The Wildland Fire Interagency Geospatial Service Interagency Fire Perimeters. National Interagency Fire Center. https://data-nifc.opendata.arcgis.com/datasets/nifc::wfigs-interagency-fire-perimeters/explore?location=0.000000%2C0.000000%2C1.82.

Forest Land Remaining Forest Land: N_2O Emissions from Soils

Albaugh, T.J., Allen, H.L., Fox, T.R. (2007) Historical Patterns of Forest Fertilization in the Southeastern United States from 1969 to 2004. Southern Journal of Applied Forestry, 31, 129-137(9).

Binkley, D. (2004) Email correspondence regarding the 95 percent confidence interval for area estimates of southern pine plantations receiving N fertilizer (±20%) and the rate applied for areas receiving N fertilizer (100 to 200 pounds/acre). Dan Binkley, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University. September 19, 2004.

Binkley, D., R. Carter, and H.L. Allen (1995) Nitrogen Fertilization Practices in Forestry. In: Nitrogen Fertilization in the Environment, P.E. Bacon (ed.), Marcel Decker, Inc., New York.

Briggs, D. (2007) Management Practices on Pacific Northwest West-Side Industrial Forest Lands, 1991-2005: With Projections to 2010. Stand Management Cooperative, SMC Working Paper Number 6, College of Forest Resources, University of Washington, Seattle.

Fox, T.R., H. L. Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson (2007) Tree Nutrition and Forest Fertilization of Pine Plantations in the Southern United States. Southern Journal of Applied Forestry, 31, 5-11.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USDA Forest Service (2001) U.S. Forest Facts and Historical Trends. FS-696. U.S. Department of Agriculture Forest Service, Washington, D.C. Available online at: http://www.fia.fs.fed.us/library/ForestFactsMetric.pdf.

Forest Land Remaining Forest Land: Drained Organic Soils

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

STATSGO2 (2016) Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2). Available online at https://sdmdataaccess.sc.egov.usda.gov. Accessed 10 November 2016.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC; 2015. Available online at https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed 30 March 2022.

USDA Forest Service (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC; 2015. Available online at https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed 30 March 2022.

Land Converted to Forest Land

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

USDA Forest Service (2023a) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 29 September 2023.

USDA Forest Service (2023b) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 29 September 2023.

USDA-NRCS (2018) Summary Report: 2015 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Land Converted to Forest Land

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." Global Change Biology 12:516-523.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

USDA Forest Service (2023b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 29 September 2023.

USDA Forest Service (2023c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://www.fia.fs.usda.gov/library/field-guides-methods-proc/index.php. Accessed on 29 September 2023.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) Summary Report: 2015 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-104.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. Scientific Reports. 5: 17028.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management 305: 48-59.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Cropland Remaining Cropland

Armentano, T. V., and E.S. Menges (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology* 74: 755-774.

Brady, N.C. and R.R. Weil (1999) The Nature and Properties of Soils. Prentice Hall. Upper Saddle River, NJ, 881.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Conant, R. T., K. Paustian, and E.T. Elliott (2001) "Grassland management and conversion into grassland: effects on soil carbon." *Ecological Applications* 11: 343-355.

CTIC (2004) National Crop Residue Management Survey: 1989-2004. Conservation Technology Information Center, Purdue University, Available online at: http://www.ctic.purdue.edu/CRM/.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) "A Statistical-Topographic Model for Mapping Climatological Precipitation Over Mountainous Terrain." *Journal of Applied Meteorology* 33:140-158.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management, L. Guo, A. Gunasekara, L. McConnell (eds.). American Chemical Society, Washington, D.C.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html.

Euliss, N., and R. Gleason (2002) Personal communication regarding wetland restoration factor estimates and restoration activity data. Ned Euliss and Robert Gleason of the U.S. Geological Survey, Jamestown, ND, to Stephen Ogle of the National Resource Ecology Laboratory, Fort Collins, CO. August 2002.

Friedman, J.H. (2001) "Greedy function approximation: A gradient boosting machine." Ann. Statist. 29 (5) 1189 – 1232.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S. M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F. E., Sanderman, J., Silvius, M., Wollenberg, E. & Fargione, J. (2017) "Natural climate solutions." Proceedings of the National Academy of Sciences of the United States of America 114(44): 11645-11650.

Hagen, S. C., G. Delgado, P. Ingraham, I. Cooke, R. Emery, J. P. Fisk, L. Melendy, T. Olson, S. Patti, N. Rubin, B. Ziniti, H. Chen, W. Salas, P. Elias, and D. Gustafson. 2020. Mapping Conservation Management Practices and Outcomes in the Corn Belt Using the Operational Tillage Information System (OpTIS) and the Denitrification–Decomposition (DNDC) Model. Land **9**:408

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

Lal, R., Kimble, J. M., Follett, R. F. & Cole, C. V. (1998) *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Sleeping Bear Press, Inc.

Little, R. (1988) "Missing-data adjustments in large surveys." *Journal of Business and Economic Statistics* 6: 287–296.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. Bulletin of the American Meteorological Society 87:343-360.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

NRCS (1981) Land Resource Regions and Major Land Resource Areas of the United States, USDA Agriculture Handbook 296, United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Cente., Lincoln, NE, pp. 156.

Ogle, S.M., Breidt, F.J., Del Grosso, S., Gurung, R., Marx, E., Spencer, S., Williams, S., Manning, D. (2023) "Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States." Scientific Reports 13(1):14564.

Ogle, S. M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F. J., McConkey, B., Regina, K. & Vazquez-Amabile, G. G. (2019) "Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions." Scientific Reports 9(1): 11665.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205:453-463.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

Ogle, S. M., et al. (2005) "Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions." *Biogeochemistry* 72: 87-121.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Paustian, K., et al. (1997a) "Agricultural soils as a sink to mitigate CO_2 emissions." *Soil Use and Management* 13: 230-244.

Paustian, K., et al. (1997b) Management controls on soil carbon. In Soil organic matter in temperate agroecosystems: long-term experiments in North America (Paul E.A., K. Paustian, and C.V. Cole, eds.). Boca Raton, CRC Press, pp. 15-49.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Pukelsheim, F. (1994) "The 3-Sigma-Rule." American Statistician 48:88-91

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

Spencer, S., S.M. Ogle, F.J. Breidt, J. Goebel, and K. Paustian. (2011) "Designing a national soil carbon monitoring network to support climate change policy: a case example for US agricultural lands." Greenhouse Gas Management & Measurement 1: 167-178.

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

USDA-ERS (2020) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (2018) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: http://www.ers.usda.gov/data/archive/93018/.

USDA Forest Service. (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 07 October 2022.

USDA-FSA (2015) Conservation Reserve Program Monthly Summary – September 2015. U.S. Department of Agriculture, Farm Service Agency, Washington, D.C. Available online at: https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/sep2015summary.pdf.

USDA-NASS (2022) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C., Accessed October 2022, http://quickstats.nass.usda.gov/.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NASS (2017) 2017 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2012) 2012 Census of Agriculture. USDA National Agricultural Statistics Service, Complete data available at http://www.nass.usda.gov/AgCensus.

USDA-NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH.

USDA-NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf.

USDA-NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa, https://www.nrcs.usda.gov/sites/default/files/2022-10/2017NRISummary_Final.pdf.

USDA-NRCS (2018) CEAP Cropland Farmer Surveys. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/na/?cid=nrcs143_014163.

USDA-NRCS (2012) Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi River Basin. U.S. Department of Agriculture, Natural Resources Conservation Service, https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1042093.pdf.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Land Converted to Cropland

Sampson and D. Hair, (eds.). *Forest and Global Change*, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) *Introduction to time series and forecasting*. Springer.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In *Modeling Carbon and Nitrogen Dynamics for Soil Management*, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) "Soil organic matter cycling and greenhouse gas accounting methodologies." Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: *Understanding Greenhouse Gas Emissions from Agricultural Management* (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.); *Modeling Carbon and Nitrogen Dynamics for Soil Management*. CRC Press. Boca Raton, Florida. 303-332.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) "Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States". *Carbon Balance and Management* 6:14.

Domke, G.M., et al. (2013) "From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory." *PLoS ONE* 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) "A framework for estimating litter carbon stocks in forests of the United States." *Science of the Total Environment* 557–558: 469–478.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) "Completion of the 2006 National Land Cover Database for the Conterminous United States." *PE&RS*, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) "Completion of the 2001 National Land Cover Database for the Conterminous United States." *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) "Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information." *Photogrammetric Engineering and Remote Sensing* 81: 345-354.

Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere." *Ecological Monographs* 53: 235-262.

Houghton, R. A. and Nassikas, A. A. (2017) "Global and regional fluxes of carbon from land use and land cover change 1850–2015." *Global Biogeochemical Cycles* 31(3): 456-472.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." *Forest Science* 49(1):12-35.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) *CENTURY Soil Organic Matter Model Environment. Agroecosystem version 4.0.* Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.Ogle, S.M., Breidt, F.J., Del Grosso, S., Gurung, R., Marx, E., Spencer, S., Williams, S., Manning, D. (2023) "Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States." Scientific Reports 13(1):14564.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in *Quantitative Modeling of Soil Forming Processes.* Special Publication 39, Soil Science Society of America, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. (2023) A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-XX

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Grassland Remaining Grassland: Soil Carbon Stock Changes

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: http://biosolids.policy.net/relatives/18941.PDF.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon (2000) Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States. U.S. Department of Agriculture, Washington, D.C. Publication number nps00-0579.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association. July 21, 2007.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. *Environmental and Ecological Statistics* 4:181-204.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 24 July 2015.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Grassland Remaining Grassland: Non-CO_2 Emissions from Grassland Fires

Anderson, R.C. Evolution and origin of the Central Grassland of North America: climate, fire and mammalian grazers. *Journal of the Torrey Botanical Society* 133: 626-647.

Andreae, M.O. and P. Merlet (2001) Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles* 15:955-966.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Chapin, F.S., S.F. Trainor, O. Huntington, A.L. Lovecraft, E. Zavaleta, D.C. Natcher, A.D. McGuire, J.L. Nelson, L. Ray, M. Calef, N. Fresco, H. Huntington, T.S. Rupp, L. DeWilde, and R.L. Naylor (2008) Increasing wildfires in Alaska's Boreal Forest: Pathways to potential solutions of a wicked problem. *Bioscience* 58:531-540.

Daubenmire, R. (1968) Ecology of fire in grasslands. *Advances in Ecological Research* 5:209-266.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

MTBS (2023) Burned Areas Boundaries Dataset. (2023, August – last revised). MTBS Project (USDA Forest Service/U.S. Geological Survey). Available online: https://mtbs.gov/direct-download Accessed: August 9, 2023.

Ogle, S.M., S. Spencer, M. Hartman, L. Buendia, L. Stevens, D. du Toit, J. Witi (2016) "Developing national baseline GHG emissions and analyzing mitigation potentials for agriculture and forestry using an advanced national GHG inventory software system." In Advances in Agricultural Systems Modeling 6, *Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forestry Systems to Guide Mitigation and Adaptation*, S. Del Grosso, L.R. Ahuja and W.J. Parton (eds.), American Society of Agriculture, Crop Society of America and Soil Science Society of America, pp. 129-148.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. *Environmental and Ecological Statistics* 4:181-204.

Picotte, J.J., K. Bhattarai, D. Howard, J. Lecker, J. Epting, B. Quayle, N. Benson, and K. Nelson (2020) "Changes to the Monitoring Trends in Burn Severity program mapping production procedures and data products." *Fire Ecology*. 16:16. https://doi.org/10.1186/s42408-020-00076-y.

USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf.

Land Converted to Grassland

Asner, G.P., Archer, S., Hughes, R.F., Ansley, R.J. and Wessman, C.A. (2003) "Net changes in regional woody vegetation cover and carbon storage in Texas drylands, 1937–1999." *Global Change Biology* 9(3): 316-335.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Breshears, D.D., Knapp, A.K., Law, D.J., Smith, M.D., Twidwell, D. and Wonkka, C.L., 2016. Rangeland Responses to Predicted Increases in Drought Extremity. Rangelands, 38(4), pp.191-196.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Del Grosso, S.J., S.M. Ogle, W.J. Parton. (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management (Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance and Management. 6:14.

Domke, G.M., et al. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., Walters, B.F., Smith, J.E., Woodall, C.W. (2022) Chapter 6: FIA Carbon Attributes. In Westfall, J.A.; Coulston, J.W.; Moisen, G.G.; Andersen, H.-E., eds. 2022. Sampling and estimation documentation for the Enhanced Forest Inventory and Analysis Program: 2022. Gen. Tech. Rep. NRS-GTR-207, Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 129 p. https://doi.org/10.2737/NRS-GTR-207.

Epstein, H.E., Gill, R.A., Paruelo, J.M., Lauenroth, W.K., Jia, G.J. and Burke, I.C. (2002) The relative abundance of three plant functional types in temperate grasslands and shrublands of North and South America: effects of projected climate change. Journal of Biogeography, 29(7), pp.875-888.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345-354.

Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere." *Ecological Monographs* 53: 235-262.

Houghton, R. A. and Nassikas, A. A. (2017) "Global and regional fluxes of carbon from land use and land cover change 1850–2015." *Global Biogeochemical Cycles* 31(3): 456-472.

Huang, C.Y., Asner, G.P., Martin, R.E., Barger, N.N. and Neff, J.C. (2009) "Multiscale analysis of tree cover and aboveground carbon stocks in pinyon-juniper woodlands." *Ecological Applications* 19(3): 668-681.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, [H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Jurena, P.N. and Archer, S., (2003) Woody plant establishment and spatial heterogeneity in grasslands. Ecology, 84(4), pp.907-919.

Lenihan, J.M., Drapek, R., Bachelet, D. and Neilson, R.P., (2003) Climate change effects on vegetation distribution, carbon, and fire in California. Ecological Applications, 13(6), pp.1667-1681.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

PRISM Climate Group (2022) PRISM Climate Data, Oregon State University, http://prism.oregonstate.edu, downloaded January 2022.

Scholes, R.J. and Archer, S.R. (1997) Tree-grass interactions in savannas 1. Annual review of Ecology and Systematics, 28(1), pp.517-544.

Sims, P.L., Singh, J.S. and Lauenroth, W.K. (1978) The structure and function of ten western North American grasslands: I. Abiotic and vegetational characteristics. The Journal of Ecology, pp.251-285.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tarhouni, M., et al. (2016) Measurement of the aboveground biomass of some rangeland species using a digital non-destructive technique. *Botany Letters* 163(3):281-287.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.

United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html.

USDA Forest Service (2023) Forest Inventory and Analysis National Program: FIA Data Mart v2.0.1. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html Accessed on 13 September 2023.

USDA-NASS (2021) Published crop data layer. Available at https://nassgeodata.gmu.edu/CropScape/, Accessed July 2021, USDA-NASS, Washington, DC.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (2018) *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." *ISPRS Journal of Photogrammetry and Remote Sensing* 146: 108-123.

Wetlands Remaining Wetlands: CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands

Apodaca, L. (2011) Email correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. November.

Apodaca, L. (2008) E-mail correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. October and November.

Cleary, J., N. Roulet and T.R. Moore (2005) "Greenhouse gas emissions from Canadian peat extraction, 1990-2000: A life-cycle analysis." *Ambio* 34:456–461.

Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014).* Alaska Department of Natural Resources, Fairbanks, AK. Available online at http://www.dggs.dnr.state.ak.us/pubs/pubs?reqtype=minerals.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. R.K. Pachauri and L.A. Meyer (eds.). IPCC, Geneva, Switzerland.

IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report (AR4) of the IPCC*. The Intergovernmental Panel on Climate Change, R.K. Pachauri, A. Resinger (eds.). Geneva, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Szumigala, D.J. (2011) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. January 18, 2011.

Szumigala, D.J. (2008) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. October 17, 2008.

USGS (1991–2018) *Minerals Yearbook: Peat (1994–2018).* United States Geological Survey, Reston, VA. Available online at http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html.

USGS (2023a) *Minerals Yearbook: Peat (2019) Tables-only release.* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023b) *Minerals Yearbook: Peat (2020) Tables-only release.* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023c) *Mineral Commodity Summaries: Peat (1996-2023).* United States Geological Survey, Reston, VA. Available online at https://www.usgs.gov/centers/nmic/peat-statistics-and-information.

USGS (2023d) Email correspondence. Amanda Brioche, Mineral Commodity Specialist, USGS. August 2023.

Wetlands Remaining Coastal Wetlands: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands

Abbott, K. M., Elsey-Quirk, T., and DeLaune, R. D. (2019) Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes. Ecosphere, 10(8): e02828.

Allen, J. R., Cornwell, J. C., and Baldwin, A. H. (2021) Contributions of organic and mineral matter to vertical accretion in tidal wetlands across a Chesapeake Bay subestuary. Journal of Marine Science and Engineering 9(7): 751.

Arias-Ortiz, A., Oikawa, P. Y., Carlin, J., Masqué, P., Shahan, J., Kanneg, S., ... and Baldocchi, D. D. (2021) Tidal and nontidal marsh restoration: a trade-off between carbon sequestration, methane emissions, and soil accretion. Journal of Geophysical Research: Biogeosciences, 126(12): e2021JG006573.

Arriola, J. M., and Cable, J. E. (2017) Variations in carbon burial and sediment accretion along a tidal creek in a Florida salt marsh. Limnology and Oceanography 62(S1): S15-S28.

Baustian, M. M., Stagg, C. L., Perry, C. L., Moss, L. C., and Carruthers, T. J. (2021) Long-term carbon sinks in marsh soils of coastal Louisiana are at risk to wetland loss. Journal of Geophysical Research: Biogeosciences 126(3): e2020JG005832.

Bianchi, T. S., Allison, M. A., Zhao, J., Li, X., Comeaux, R. S., Feagin, R. A., & Kulawardhana, R. W. (2013) Historical reconstruction of mangrove expansion in the Gulf of Mexico: linking climate change with carbon sequestration in coastal wetlands. Estuarine, Coastal and Shelf Science 119: 7-16.

Boyd, B. (2012) Comparison of sediment accumulation and accretion in impounded and unimpounded marshes of the Delaware Estuary. Doctoral dissertation, University of Delaware.

Boyd, B. M. and Sommerfield, C. K. (2016) Marsh accretion and sediment accumulation in a managed tidal wetland complex of Delaware Bay. Ecological Engineering, 92: 37-46.

Boyd, B. M., Sommerfield, C. K., and Elsey-Quirk, T. (2017) Hydrogeomorphic influences on salt marsh sediment

accumulation and accretion in two estuaries of the US Mid-Atlantic coast. Marine Geology, 383: 132-145.

Breithaupt, J. L., Smoak, J. M., Smith III, T. J., and Sanders, C. J. (2014) Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades. Journal of Geophysical Research: Biogeosciences, 119(10): 2032-2048.

Byrd, K. B., Ballanti, L. R., Thomas, N. M., Nguyen, D. K., Holmquist, J. R., Simard, M., Windham-Myers, L., Schile, L. M., Parker, V. T., … and Castaneda-Moya, E. (2017) Biomass/Remote Sensing dataset: 30m resolution tidal marsh biomass samples and remote sensing data for six regions in the conterminous United States: U.S. Geological Survey data release, https://doi.org/10.5066/F77943K8.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2018) A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS Journal of Photogrammetry and Remote Sensing 139: 255-271.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2020) Corrigendum to “A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States”. ISPRS Journal of Photogrammetry and Remote Sensing 166: 63-67.

Callaway, J. C., Borgnis, E. L., Turner, R. E. & Milan, C. S. (2012a) Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries and Coasts 35(5): 1163-1181.

Callaway, J. C., Borgnis, E. L., Turner, R. E., Milan, C. S., Goodfriend, W., & Richmond, S. (2012b) "Wetland Sediment Accumulation at Corte Madera Marsh and Muzzi Marsh". San Francisco Bay Conservation and Development Commission.

Church, T. M., Sommerfield, C. K., Velinsky, D. J., Point, D., Benoit, C., Amouroux, D. & Donard, O. F. X. (2006) Marsh sediments as records of sedimentation, eutrophication and metal pollution in the urban Delaware Estuary. Marine Chemistry 102(1-2): 72-95.

Couvillion, B. R., Barras, J. A., Steyer, G. D., Sleavin, W., Fischer, M., Beck, H., & Heckman, D. (2011) Land area change in coastal Louisiana (1932 to 2010) (pp. 1-12). U.S. Department of the Interior, U.S. Geological Survey.

Couvillion, B. R., Fischer, M. R., Beck, H. J. and Sleavin, W. J. (2016) Spatial Configuration Trends in Coastal Louisiana from 1986 to 2010. Wetlands 1-13.

Craft, C. B., & Richardson, C. J. (1998) Recent and long-term organic soil accretion and nutrient accumulation in the Everglades. Soil Science Society of America Journal 62(3): 834-843.

Crooks, S., Findsen, J., Igusky, K., Orr, M. K. and Brew, D. (2009) Greenhouse Gas Mitigation Typology Issues Paper: Tidal Wetlands Restoration. Report by PWA and SAIC to the California Climate Action Reserve.

Crooks, S., Rybczyk, J., O’Connell, K., Devier, D. L., Poppe, K., Emmett-Mattox, S. (2014) Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration. Report by Environmental Science Associates, Western Washington University, EarthCorps, and Restore America’s Estuaries.

DeLaune, R. D., & White, J. R. (2012) Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: A case study of the rapidly subsiding Mississippi river deltaic plain. Climatic Change, 110(1), 297-314.

Drexler, J. Z., de Fontaine, C. S., and Brown, T. A. (2009) Peat accretion histories during the past 6,000 years in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries and Coasts 32: 871-892.

Drexler, J. Z., Krauss, K. W., Sasser, M. C., Fuller, C. C., Swarzenski, C. M., Powell, A., ... and Orlando, J. (2013) A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. Wetlands 33: 965-974.

Drexler, J. Z., Woo, I., Fuller, C. C., and Nakai, G. (2019) Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States. Restoration Ecology 27(5): 1117-1127.

Ensign, S. H., Noe, G. B., Hupp, C. R., and Skalak, K. J. (2015) Head-of-tide bottleneck of particulate material transport from watersheds to estuaries. Geophysical Research Letters 42(24): 10-671.

Gerlach, M. J., Engelhart, S. E., Kemp, A. C., Moyer, R. P., Smoak, J. M., Bernhardt, C. E., and Cahill, N. (2017) Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. Marine Geology 390: 254-269.

Giblin, A., Forbrich, I., & LTER, P. I. E. (2018) PIE LTER high marsh sediment chemistry and activity measurements, Nelson Island Creek marsh, Rowley, MA.

Holmquist, J. R., Windham-Myers, L., Bliss, N., Crooks, S., Morris, J. T., Megonigal, J. P. & Woodrey, M. (2018) Accuracy and Precision of Tidal Wetland Soil Carbon Mapping in the Conterminous United States. Scientific reports 8(1): 9478.

Hu, Z., Lee, J. W., Chandran, K., Kim, S. and Khanal, S. K. (2012) N_2O Emissions from Aquaculture: A Review. Environmental Science & Technology 46(12): 6470-6480.

Hussein, A. H., Rabenhorst, M. C. & Tucker, M. L. (2004) Modeling of carbon sequestration in coastal marsh soils. Soil Science Society of America Journal 68(5): 1786-1795.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Stocker, T., Qin, D., Plattner, G.-K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Quantifying Uncertainties in Practice, Chapter 6. Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., Emmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., Miwa, K. and Tanabe, K. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Kearney, M. S. & Stevenson, J. C. (1991) Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. Journal of Coastal Research 7(2): 403-415.

Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S., and Nikitina, D. (2012) Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology 12: 40-49.

Köster, D., Lichter, J., Lea, P. D., & Nurse, A. (2007) Historical eutrophication in a river–estuary complex in mid-coast Maine. Ecological Applications 17(3): 765-778.

Krauss, K. W., Noe, G. B., Duberstein, J. A., Conner, W. H., Stagg, C. L., and Jones, M. C. (2018) Carbon budget assessment of tidal freshwater forested wetland and oligohaline marsh ecosystems along the Waccamaw and Savannah Rivers, USA (2005–2016). US Geological Survey Data Release. https://doi.Org/10.5066/F7TM7930.

Lagomasino, D., Corbett, D. R., and Walsh, J. P. (2013) Influence of wind-driven inundation and coastal geomorphology on sedimentation in two microtidal marshes, Pamlico River Estuary, NC. Estuaries and Coasts 36: 1165-1180.

Lu, M & Megonigal, J. P. (2017) Final Report for RAE Baseline Assessment Project. Memo to Silvestrum Climate

Associates by Smithsonian Environmental Research Center, Maryland.

Lynch, J. C. (1989) Sedimentation and nutrient accumulation in mangrove ecosystems of the Gulf of Mexico. M.S. thesis, Univ. of Southwestern Louisiana, Lafayette, LA.

Luk, S. Y., Todd-Brown, K., Eagle, M., McNichol, A. P., Sanderman, J., Gosselin, K., and Spivak, A. C. (2021) Soil organic carbon development and turnover in natural and disturbed salt marsh environments. Geophysical Research Letters 48(2): e2020GL090287.

Marchio, D. A., Savarese, M., Bovard, B., & Mitsch, W. J. (2016) Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida. Forests 7: 116-135.

McCombs, J. W., Herold, N. D., Burkhalter, S. G. and Robinson C. J. (2016) Accuracy Assessment of NOAA Coastal Change Analysis Program 2006-2010 Land Cover and Land Cover Change Data. Photogrammetric Engineering & Remote Sensing. 82:711-718.

McTigue, N., Davis, J., Rodriguez, A. B., McKee, B., Atencio, A., and Currin, C. (2019) Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia. JGR Biogeosciences.

Merrill, J. Z. (1999) Tidal Freshwater Marshes as Nutrient Sinks: particulate Nutrient Burial and Denitrification. Ph.D. Dissertation, University of Maryland, College Park, MD, 342 pp.

Miller, C. B., Rodriguez, A. B., Bost, M. C., McKee, B. A., and McTigue, N. D. (2022) Carbon accumulation rates are highest at young and expanding salt marsh edges. Communications Earth & Environment 3(1): 173.

National Marine Fisheries Service (2022). Fisheries of the United States, 2020. U.S. Department of Commerce, NOAA Current Fishery Statistics No. 2020. Available at: https://www.fisheries.noaa.gov/ national/sustainable-fisheries/fisheries-united-states.

National Oceanic and Atmospheric Administration, Office for Coastal Management (2020) Coastal Change Analysis Program (C-CAP) Regional Land Cover. Charleston, SC: NOAA Office for Coastal Management. Accessed October 2020 at www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/.

Noe, G. B., Hupp, C. R., Bernhardt, C. E., & Krauss, K. W. (2016) Contemporary deposition and long-term accumulation of sediment and nutrients by tidal freshwater forested wetlands impacted by sea level rise. Estuaries and Coasts 39(4): 1006-1019.

Orson, R. A., Simpson, R. L., & Good, R. E. (1990) Rates of sediment accumulation in a tidal freshwater marsh. Journal of Sedimentary Research 60(6): 859-869.

Orson, R., Warren, R. & Niering, W. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine, Coastal and Shelf Science 47(4): 419-429.

Peck, E. K., Wheatcroft, R. A., and Brophy, L. S. (2020) Controls on sediment accretion and blue carbon burial in tidal saline wetlands: insights from the Oregon Coast, USA. Journal of Geophysical Research: Biogeosciences 125(2): e2019JG005464.

Poppe, K. L., and Rybczyk, J. M. (2021) Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington. PloS one 16(9): e0257244.

Roman, C., Peck, J., Allen, J., King, J. & Appleby, P. (1997) Accretion of a New England (USA) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45(6): 717-727.

Smith, K. E., Flocks, J. G., Steyer, G. D., and Piazza, S. C. (2015) Wetland Paleoecological Study of Southwest Coastal Louisiana: Sediment Cores and Diatom Calibration Dataset. US Department of the Interior, US Geological Survey.

Thom, R. M. (1992) Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands 12: 147-156.

Vaughn, D. R., Bianchi, T. S., Shields, M. R., Kenney, W. F., and Osborne, T. Z. (2020) Increased organic carbon burial in northern Florida mangrove-salt marsh transition zones. Global Biogeochemical Cycles 34(5): e2019GB006334.

Villa, J. A. & Mitsch W. J. (2015) Carbon sequestration in different wetland plant communities of Southwest Florida. International Journal for Biodiversity Science, Ecosystems Services and Management 11: 17-28

Watson, E. B., and Byrne, R. (2013) Late Holocene Marsh Expansion in Southern San Francisco Bay, California. Estuaries and Coasts 36: 643-653.

Weis, D. A., Callaway, J. C., and Gersberg, R. M. (2001) Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. Estuaries 24: 840-850.

Weston, N. B., Neubauer, S. C., Velinsky, D. J., & Vile, M. A. (2014) Net ecosystem carbon exchange and the greenhouse gas balance of tidal marshes along an estuarine salinity gradient. Biogeochemistry 120: 163-189.

Weston, N. B., Rodriguez, E., Donnelly, B., Solohin, E., Jezycki, K., Demberger, S., ... and Craft, C. B. (2023) Recent acceleration of wetland accretion and carbon accumulation along the US East Coast. Earth's Future 11(3): e2022EF003037.

Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land

Abril, G., Gu´erin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., et al. (2005) Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem. Cycles 19 (GB4007), 1–16. https://doi.org/10.1029/2005GB002457.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., et al. (2011) Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4 (9), 593–596. https://doi.org/10.1038/ngeo1211.

Davis, D. W. (1973) Louisiana Canals and Their Influence on Wetland Development. Louisiana State University and Agricultural & Mechanical College. LSU Historical Dissertations and Theses. 2386., Louisiana State University.

IPCC (2019) 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories. Wetlands, Chapter 7. Lovelock, C. E., Evans, C., Barros, N., Prairie, Y. T., Alm, J., Bastviken, D., Beaulieu, J. J., Garneau, M., Harby, A., Harrison, J. A., Pare, David, Raadal, Hanne Lerche, Sherman, B., Zhang, Chengyi, Ogle, S. M.IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.* Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). In: IPCC, Switzerland.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Lehner B, Reidy Liermann C, Revenga C, Vorosmarty C, Fekete B, Crouzet P, Doll P, et al. (2011b) Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. In: Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Prairie, Y. T., et al. (2017) The GHG Reservoir Tool (G-res) User guide. UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association: 38.

Teodoru, C.R., Bastien, J., Bonneville, M.C., Del Giorgio, P.a., Demarty, M., Garneau, M., et al., 2012. The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem. Cycles 26 (GB2016), 1–14. https://doi.org/10.1029/2011GB004187.

Land Converted to Wetlands: Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Abbott, K. M., Elsey-Quirk, T., and DeLaune, R. D. (2019) Factors influencing blue carbon accumulation across a 32-year chronosequence of created coastal marshes. Ecosphere, 10(8): e02828.

Allen, J. R., Cornwell, J. C., and Baldwin, A. H. (2021) Contributions of organic and mineral matter to vertical accretion in tidal wetlands across a Chesapeake Bay subestuary. Journal of Marine Science and Engineering 9(7): 751.

Arias-Ortiz, A., Oikawa, P. Y., Carlin, J., Masqué, P., Shahan, J., Kanneg, S., ... and Baldocchi, D. D. (2021) Tidal and nontidal marsh restoration: a trade-off between carbon sequestration, methane emissions, and soil accretion. Journal of Geophysical Research: Biogeosciences, 126(12): e2021JG006573.

Arriola, J. M., and Cable, J. E. (2017) Variations in carbon burial and sediment accretion along a tidal creek in a Florida salt marsh. Limnology and Oceanography 62(S1): S15-S28.

Baustian, M. M., Stagg, C. L., Perry, C. L., Moss, L. C., and Carruthers, T. J. (2021) Long-term carbon sinks in marsh soils of coastal Louisiana are at risk to wetland loss. Journal of Geophysical Research: Biogeosciences 126(3): e2020JG005832.

Bianchi, T. S., Allison, M. A., Zhao, J., Li, X., Comeaux, R. S., Feagin, R. A., & Kulawardhana, R. W. (2013) Historical reconstruction of mangrove expansion in the Gulf of Mexico: linking climate change with carbon sequestration in coastal wetlands. Estuarine, Coastal and Shelf Science 119: 7-16.

Boyd, B. (2012) Comparison of sediment accumulation and accretion in impounded and unimpounded marshes of the Delaware Estuary. Doctoral dissertation, University of Delaware.

Boyd, B. M. and Sommerfield, C. K. (2016) Marsh accretion and sediment accumulation in a managed tidal wetland complex of Delaware Bay. Ecological Engineering, 92: 37-46.

Boyd, B. M., Sommerfield, C. K., and Elsey-Quirk, T. (2017) Hydrogeomorphic influences on salt marsh sediment accumulation and accretion in two estuaries of the US Mid-Atlantic coast. Marine Geology, 383: 132-145.

Breithaupt, J. L., Smoak, J. M., Smith III, T. J., and Sanders, C. J. (2014) Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades. Journal of Geophysical Research: Biogeosciences, 119(10): 2032-2048.

Byrd, K. B., Ballanti, L. R., Thomas, N. M., Nguyen, D. K., Holmquist, J. R., Simard, M., Windham-Myers, L., Schile, L. M., Parker, V. T., … and Castaneda-Moya, E. (2017) Biomass/Remote Sensing dataset: 30m resolution tidal marsh biomass samples and remote sensing data for six regions in the conterminous United States: U.S. Geological Survey data release, https://doi.org/10.5066/F77943K8.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2018) A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. ISPRS Journal of Photogrammetry and Remote Sensing 139: 255-271.

Byrd, K. B., Ballanti, L., Thomas, N., Nguyen, D., Holmquist, J.R., Simard, M., and Windham-Myers, L. (2020) Corrigendum to “A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States”. ISPRS Journal of Photogrammetry and Remote Sensing 166: 63-67.

Callaway, J. C., Borgnis, E. L., Turner, R. E. & Milan, C. S. (2012a) Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries and Coasts 35(5): 1163-1181.

Callaway, J. C., Borgnis, E. L., Turner, R. E., Milan, C. S., Goodfriend, W., & Richmond, S. (2012b) "Wetland Sediment Accumulation at Corte Madera Marsh and Muzzi Marsh". San Francisco Bay Conservation and Development Commission.

Church, T. M., Sommerfield, C. K., Velinsky, D. J., Point, D., Benoit, C., Amouroux, D. & Donard, O. F. X. (2006) Marsh sediments as records of sedimentation, eutrophication and metal pollution in the urban Delaware Estuary. Marine Chemistry 102(1-2): 72-95.

Craft, C. B., & Richardson, C. J. (1998) Recent and long-term organic soil accretion and nutrient accumulation in the Everglades. Soil Science Society of America Journal 62(3): 834-843.

Crooks, S., Rybczyk, J., O'Connell, K., Devier, D.L., Poppe, K., Emmett-Mattox, S. (2014) Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration. Report by Environmental Science Associates, Western Washington University, EarthCorps, and Restore America's Estuaries.

Drexler, J. Z., de Fontaine, C. S., and Brown, T. A. (2009) Peat accretion histories during the past 6,000 years in marshes of the Sacramento–San Joaquin Delta, CA, USA. Estuaries and Coasts 32: 871-892.

Drexler, J. Z., Krauss, K. W., Sasser, M. C., Fuller, C. C., Swarzenski, C. M., Powell, A., ... and Orlando, J. (2013) A long-term comparison of carbon sequestration rates in impounded and naturally tidal freshwater marshes along the lower Waccamaw River, South Carolina. Wetlands 33: 965-974.

Drexler, J. Z., Woo, I., Fuller, C. C., and Nakai, G. (2019) Carbon accumulation and vertical accretion in a restored versus historic salt marsh in southern Puget Sound, Washington, United States. Restoration Ecology 27(5): 1117-1127.

Ensign, S. H., Noe, G. B., Hupp, C. R., and Skalak, K. J. (2015) Head-of-tide bottleneck of particulate material transport from watersheds to estuaries. Geophysical Research Letters 42(24): 10-671.

Gerlach, M. J., Engelhart, S. E., Kemp, A. C., Moyer, R. P., Smoak, J. M., Bernhardt, C. E., and Cahill, N. (2017) Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. Marine Geology 390: 254-269.

Giblin, A., Forbrich, I., & LTER, P. I. E. (2018) PIE LTER high marsh sediment chemistry and activity measurements, Nelson Island Creek marsh, Rowley, MA.

Hussein, A. H., Rabenhorst, M. C. & Tucker, M. L. (2004) Modeling of carbon sequestration in coastal marsh soils. Soil Science Society of America Journal 68(5): 1786-1795.

IPCC (2019) *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 4: Agriculture, Forestry, and Other Land Use. Calvo Buendia, E., Tanabe K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., & Federici, S. (eds). IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, H.S.Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (eds). IGES, Japan.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.). Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T., Qin, D., Plattner, G.-K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. & F. Wagner (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Quantifying Uncertainties in Practice, Chapter 6. Penman, J and Kruger, D and Galbally, I and Hiraishi, T and Nyenzi, B and Emmanuel, S and Buendia, L and Hoppaus, R and Martinsen, T and Meijer, J and Miwa, K and Tanabe, K (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate

Change (IPCC): Hayama, Japan.

Kearney, M. S. & Stevenson, J. C. (1991) Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. Journal of Coastal Research 7(2): 403-415.

Kemp, A. C., Sommerfield, C. K., Vane, C. H., Horton, B. P., Chenery, S., Anisfeld, S., and Nikitina, D. (2012) Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology 12: 40-49.

Köster, D., Lichter, J., Lea, P. D., & Nurse, A. (2007) Historical eutrophication in a river–estuary complex in mid-coast Maine. Ecological Applications 17(3): 765-778.

Krauss, K. W., Noe, G. B., Duberstein, J. A., Conner, W. H., Stagg, C. L., and Jones, M. C. (2018) Carbon budget assessment of tidal freshwater forested wetland and oligohaline marsh ecosystems along the Waccamaw and Savannah Rivers, USA (2005–2016). US Geological Survey Data Release. https://doi.Org/10.5066/F7TM7930.

Lagomasino, D., Corbett, D. R., and Walsh, J. P. (2013) Influence of wind-driven inundation and coastal geomorphology on sedimentation in two microtidal marshes, Pamlico River Estuary, NC. Estuaries and Coasts 36: 1165-1180.

Lu, M & Megonigal, J.P. (2017) Final Report for RAE Baseline Assessment Project. Memo to Silvestrum Climate Associates by Smithsonian Environmental Research Center, Maryland.

Lynch, J. C. (1989) Sedimentation and nutrient accumulation in mangrove ecosystems of the Gulf of Mexico, M.S. thesis, Univ. of Southwestern Louisiana, Lafayette, La.

Luk, S. Y., Todd-Brown, K., Eagle, M., McNichol, A. P., Sanderman, J., Gosselin, K., and Spivak, A. C. (2021) Soil organic carbon development and turnover in natural and disturbed salt marsh environments. Geophysical Research Letters 48(2): e2020GL090287.

Marchio, D.A., Savarese, M., Bovard, B., & Mitsch, W.J. (2016) Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida. Forests 7: 116-135.

McCombs, J.W., Herold, N.D., Burkhalter, S.G. and Robinson C.J., (2016) Accuracy Assessment of NOAA Coastal Change Analysis Program 2006-2010 Land Cover and Land Cover Change Data. Photogrammetric Engineering & Remote Sensing. 82:711-718.

McTigue, N., Davis, J., Rodriguez, A. B., McKee, B., Atencio, A., and Currin, C. (2019) Sea level rise explains changing carbon accumulation rates in a salt marsh over the past two millennia. JGR Biogeosciences.

Merrill, J. Z. (1999) Tidal Freshwater Marshes as Nutrient Sinks: particulate Nutrient Burial and Denitrification. Ph.D. Dissertation, University of Maryland, College Park, MD, 342pp.

Miller, C. B., Rodriguez, A. B., Bost, M. C., McKee, B. A., and McTigue, N. D. (2022) Carbon accumulation rates are highest at young and expanding salt marsh edges. Communications Earth & Environment 3(1): 173.

National Oceanic and Atmospheric Administration, Office for Coastal Management (2020) Coastal Change Analysis Program (C-CAP) Regional Land Cover. Charleston, SC: NOAA Office for Coastal Management. Accessed October 2020 at www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/.

Noe, G. B., Hupp, C. R., Bernhardt, C. E., & Krauss, K. W. (2016) Contemporary deposition and long-term accumulation of sediment and nutrients by tidal freshwater forested wetlands impacted by sea level rise. Estuaries and Coasts 39(4): 1006-1019.

Orson, R. A., Simpson, R. L., & Good, R. E. (1990) Rates of sediment accumulation in a tidal freshwater marsh. Journal of Sedimentary Research 60(6): 859-869.

Orson, R., Warren, R. & Niering, W. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine, Coastal and Shelf Science 47(4): 419-429.

Peck, E. K., Wheatcroft, R. A., and Brophy, L. S. (2020) Controls on sediment accretion and blue carbon burial in

tidal saline wetlands: insights from the Oregon Coast, USA. Journal of Geophysical Research: Biogeosciences 125(2): e2019JG005464.

Poppe, K. L., and Rybczyk, J. M. (2021) Tidal marsh restoration enhances sediment accretion and carbon accumulation in the Stillaguamish River estuary, Washington. PloS one 16(9): e0257244.

Roman, C., Peck, J., Allen, J., King, J. & Appleby, P. (1997) Accretion of a New England (USA) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45(6): 717-727.

Smith, K. E., Flocks, J. G., Steyer, G. D., and Piazza, S. C. (2015) Wetland Paleoecological Study of Southwest Coastal Louisiana: Sediment Cores and Diatom Calibration Dataset. US Department of the Interior, US Geological Survey.

Thom, R. M. (1992 Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands 12: 147-156.

Vaughn, D. R., Bianchi, T. S., Shields, M. R., Kenney, W. F., and Osborne, T. Z. (2020) Increased organic carbon burial in northern Florida mangrove-salt marsh transition zones. Global Biogeochemical Cycles 34(5): e2019GB006334.

Villa, J. A. & Mitsch W. J. (2015) "Carbon sequestration in different wetland plant communities of Southwest Florida". International Journal for Biodiversity Science, Ecosystems Services and Management 11: 17-28.

Watson, E. B., and Byrne, R. (2013) Late Holocene Marsh Expansion in Southern San Francisco Bay, California. Estuaries and Coasts 36: 643-653.

Weis, D. A., Callaway, J. C., and Gersberg, R. M. (2001) Vertical accretion rates and heavy metal chronologies in wetland sediments of the Tijuana Estuary. Estuaries 24: 840-850.

Weston, N. B., Neubauer, S. C., Velinsky, D. J., & Vile, M. A. (2014) Net ecosystem carbon exchange and the greenhouse gas balance of tidal marshes along an estuarine salinity gradient. Biogeochemistry 120: 163-189.

Weston, N. B., Rodriguez, E., Donnelly, B., Solohin, E., Jezycki, K., Demberger, S., ... and Craft, C. B. (2023) Recent acceleration of wetland accretion and carbon accumulation along the US East Coast. Earth's Future 11(3): e2022EF003037.

Land Converted to Wetlands: Land Converted to Flooded Land

Abril, G., Gu´erin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., et al. (2005) Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem. Cycles 19 (GB4007), 1–16. https://doi.org/10.1029/2005GB002457.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., et al. (2011). Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4 (9), 593–596. https://doi.org/10.1038/ngeo1211.

IPCC (2019) *2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories*. Wetlands, Chapter 7. Lovelock, C. E., Evans, C., Barros, N., Prairie, Y. T., Alm, J., Bastviken, D., Beaulieu, J. J., Garneau, M., Harby, A., Harrison, J. A., Pare, David, Raadal, Hanne Lerche, Sherman, B., Zhang, Chengyi, Ogle, S. M.

IPCC (2013) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). In: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, H.S.Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (eds). IGES, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. LUCF Sector Good Practice Guidance, Chapter 3. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Institute of Global Environmental Strategies (IGES), on behalf of the Intergovernmental Panel on Climate Change (IPCC): Hayama, Japan.

Lehner B, Reidy Liermann C, Revenga C, Vorosmarty C, Fekete B, Crouzet P, Doll P, et al. (2011b) Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. In: Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Prairie, Y. T., et al. (2017) The GHG Reservoir Tool (G-res) User guide. UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association**:** 38.

Teodoru, C.R., Bastien, J., Bonneville, M.C., Del Giorgio, P.a., Demarty, M., Garneau, M., et al. (2012). The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem. Cycles 26 (GB2016), 1–14. https://doi.org/10.1029/2011GB004187.

Settlements Remaining Settlements: Soil Carbon Stock Changes

AAPFCO (2016 through 2022) Commercial Fertilizers: 2013-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

Armentano, T. V., and E.S. Menges (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. Journal of Ecology 74: 755-774.

Brady, N.C. and R.R. Weil (1999) The Nature and Properties of Soils. Prentice Hall. Upper Saddle River, NJ, 881.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing 73(4): 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81(5):345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

Nusser, S.M. and J.J. Goebel (1997) The national resources inventory: a long-term multi-resource monitoring programme. Environmental and Ecological Statistics 4:181-204.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997. Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model. Global Change Biology 16:810-822.

Särndal C-E, Swensson B, Wretman, J (1992). Model Assisted Survey Sampling. Springer, New York.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Settlements Remaining Settlements: Changes in Carbon Stocks in Settlement Trees

deVries R.E. (1987) A Preliminary Investigation of the Growth and Longevity of Trees in Central Park. M.S. thesis, Rutgers University, New Brunswick, NJ.

Fleming, L.E. (1988) Growth Estimation of Street Trees in Central New Jersey. M.S. thesis, Rutgers University, New Brunswick, NJ.

Frelich, L.E. (1992) Predicting Dimensional Relationships for Twin Cities Shade Trees. University of Minnesota, Department of Forest Resources, St. Paul, MN, p. 33.

IPCC (2006) *2006 IPCC Guidelines* for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

MRLC (2013) National Land Cover Database 2001 (NLCD2001). Available online at: http://www.mrlc.gov/nlcd2001.php. Accessed August 2013.

Nowak, D.J. (1986) Silvics of an Urban Tree Species: Norway maple (Acer platanoides L.). M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J. (1994) Atmospheric carbon dioxide reduction by Chicago's urban forest. In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.). General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (2012) Contrasting natural regeneration and tree planting in 14 North American cities. Urban Forestry and Urban Greening. 11: 374– 382.

Nowak, D.J. and D.E. Crane (2002) Carbon storage and sequestration by urban trees in the United States. Environmental Pollution 116(3):381–389.

Nowak, D.J. and E. Greenfield (2010) Evaluating the National Land Cover Database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates. Environmental Management. 46: 378-390.

Nowak, D.J. and E.J. Greenfield (2018a) U.S. urban forest statistics, values and projections. Journal of Forestry. 116(2):164–177

Nowak, D.J. and E.J. Greenfield (2018b) Declining urban and community tree cover in the United States. Urban Forestry and Urban Greening. 32:32-55.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) Brooklyn's Urban Forest. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., R.E. Hoehn, D.E. Crane, J.C. Stevens, J.T. Walton, and J. Bond (2008) A ground-based method of assessing urban forest structure and ecosystem services. Arboric. Urb. For. 34(6): 347-358.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, and E. Lapoint (2013) Carbon storage and sequestration by trees in urban and community areas of the United States." Environmental Pollution 178: 229-236.

Nowak, D.J. A.R. Bodine, R.E. Hoehn, C.B. Edgar, D.R. Hartel, T.W. Lister, T.J. Brandeis (2016) Austin's Urban Forest, 2014. USDA Forest Service, Northern Research Station Resources Bulletin. NRS-100. Newtown Square, PA. 55 p.

Nowak, D.J. A.R. Bodine, R.E. Hoehn, C.B. Edgar, G. Riley, D.R. Hartel, K.J. Dooley, S.M. Stanton, M.A. Hatfield, T.J. Brandeis, T.W. Lister (2017) Houston's Urban Forest, 2015. USDA Forest Service, Southern Research Station Resources Bulletin. SRS-211. Newtown Square, PA. 91 p.

Smith, W.B. and S.R. Shifley (1984) Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

U.S. Department of Interior (2018) National Land Cover Database 2011 (NLCD2011). Accessed online August 16, 2018. Available online at: https://www.mrlc.gov/nlcd11_leg.php.

Settlements Remaining Settlements: N_2O Emissions from Soils

AAPFCO (2016 through 2022) Commercial Fertilizers: 2013-2017. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

Brakebill, J.W. and Gronberg, J.M. (2017) County-Level Estimates of Nitrogen and Phosphorus from Commercial Fertilizer for the Conterminous United States, 1987-2012. U.S. Geological Survey, https://doi.org/10.5066/F7H41PKX.

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nelson, Mark D.; Riitters, Kurt H.; Coulston, John W.; Domke, Grant M.; Greenfield, Eric J.; Langner, Linda L.; Nowak, David J.; O'Dea, Claire B.; Oswalt, Sonja N.; Reeves, Matthew C.; Wear, David N. 2020. Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/NRS-GTR-191.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model. Global Change Biology 16:810-822.

Särndal C-E, Swensson B, Wretman, J (1992). Model Assisted Survey Sampling. Springer, New York.

Soil Survey Staff (2020) Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, Accessed February 2020 (FY2020 official release), Available online at https://gdg.sc.egov.usda.gov/.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/

Yang, L., et al. (2018). "A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies." ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Settlements Remaining Settlements: Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills

Barlaz, M.A. (2008) "Re: Corrections to Previously Published Carbon Storage Factors." Memorandum to Randall Freed, ICF International. February 28, 2008.

Barlaz, M.A. (2005) "Decomposition of Leaves in Simulated Landfill." Letter report to Randall Freed, ICF Consulting. June 29, 2005.

Barlaz, M.A. (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

De la Cruz, F.B. and M.A. Barlaz (2010) "Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data" *Environmental Science & Technology* 44:4722– 4728.

Eleazer, W.E., W.S. Odle, Y. Wang, and M.A. Barlaz (1997) "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Environmental Science & Technology* 31:911–917.

EPA (2020) *Advancing Sustainable Materials Management: Facts and Figures 2018*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report.

EPA (2019) *Advancing Sustainable Materials Management: Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report.

EPA (2016) *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/msw99.html.

EPA (1995) *Compilation of Air Pollutant Emission Factors*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. AP-42 Fifth Edition. Available online at http://www3.epa.gov/ttnchie1/ap42/.

EPA (1991) *Characterization of Municipal Solid Waste in the United States: 1990 Update*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. EPA/530-SW-90-042.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman et al. (eds.). Available online at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

Oshins, C. and D. Block (2000) "Feedstock Composition at Composting Sites." *Biocycle* 41(9):31–34.

Tchobanoglous, G., H. Theisen, and S.A. Vigil (1993) *Integrated Solid Waste Management, 1st edition*. McGraw-Hill, NY. Cited by Barlaz (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

Land Converted to Settlements

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

Brockwell, Peter J., and Richard A. Davis (2016) Introduction to time series and forecasting. Springer. Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance and Management. 6:14.

Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE 8(3): e59949.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. Science of the Total Environment 557–558: 469–478.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." Forest Science 49(1):12-35.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." Global Change Biology 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) “Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments.” Global Change Biology 12:516-523.

Schimel, D.S. (1995) "Terrestrial ecosystems and the carbon cycle." Global Change Biology 1: 77-91.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." Global Change Biology 21:2655-2660.

USDA Forest Service. (2022) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: https://apps.fs.usda.gov/fia/datamart/datamart.html. Accessed on 07 October 2022.

USDA-NRCS (2020) Summary Report: 2017 National Resources Inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/results/.

USDA-NRCS (1997) “National Soil Survey Laboratory Characterization Data,” Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

Westfall, J.A., Coulston, J.W., Gray, A.N., Shaw, J.D., Radtke, P.J., Walker, D.M., Weiskittel, A.R., MacFarlane, D.W., Affleck, D.L.R., Zhao, D., Temesgen, H., Poudel, K.P., Frank, J.M., Prisley, S.P., Wang, Y., Sánchez Meador, A.J., Auty, D., and Domke, G.M. 2023. A national-scale tree volume, biomass, and carbon modeling system for the United States. Gen. Tech. Rep. WO-XX.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G. C., Rigge, M. & Xian, G. (2018) A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS Journal of Photogrammetry and Remote Sensing 146: 108-123.

Waste

Landfills

40 CFR Part 60, Subpart WWW (2005) Standards of Performance for Municipal Solid Waste Landfills, 60.750--60.759, Code of Federal Regulations, Title 40. Available online at: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-WWW.

40 CFR Part 258, Subtitle D of RCRA (2012) Criteria for Municipal Solid Waste Landfills, 258.1—258.75, Code of Federal Regulations, Title 40. Available online at: https://www.ecfr.gov/cgi-bin/text-idx?node=pt40.25.258..

BioCycle (2010) "The State of Garbage in America" By L. Arsova, R. Van Haaren, N. Goldstein, S. Kaufman, and N. Themelis. *BioCycle.* December 2010. Available online at: https://www.biocycle.net/2010/10/26/the-state-of-garbage-in-america-4/.

Bronstein, K., Coburn, J., and R. Schmeltz (2012) "Understanding the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks and Mandatory GHG Reporting Program for Landfills: Methodologies, Uncertainties, Improvements and Deferrals." Prepared for the U.S. EPA International Emissions Inventory Conference, August 2012, Tampa, Florida. Available online at: https://www3.epa.gov/ttnchie1/conference/ei20/session3/kbronstein.pdf.

Czepiel, P., B. Mosher, P. Crill, and R. Harriss (1996) "Quantifying the Effect of Oxidation on Landfill Methane Emissions." *Journal of Geophysical Research*, 101(D11):16721-16730.Dou, Z.; Ferguson, J. D.; Galligan, D. T.; Kelly, A. M.; Finn, S. T.; Giegengack, R. (2016) "Assessing U.S. food wastage and opportunities for reduction." Global Food Security Volume 8, March 2016, Pages 19-26. https://doi.org/10.1016/j.gfs.2016.02.001.

EIA (2007) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2006). Available online at: https://www.eia.gov/environment/pdfpages/0608s(2009)index.php.

EPA (2023a) Greenhouse Gas Reporting Program (GHGRP). 2022 Amazon S3 Data. Subpart HH: Municipal Solid Waste Landfills and Subpart TT: Industrial Waste Landfills. Accessed on August 8, 2023.

EPA (2023b) Landfill Methane Outreach Program (LMOP). 2023 Landfill and Project Level Data. July 2023. Available online at: https://www.epa.gov/lmop/landfill-gas-energy-project-data.

EPA (2020a) Wasted Food Measurement Methodology Scoping Memo. July 2020. Available online at https://www.epa.gov/sites/production/files/2020-06/documents/food_measurement_methodology_scoping_memo-6-18-20.pdf.

EPA (2020b) Advancing Sustainable Materials Management: Facts and Figures 2018. December 2020. Available online at: https://www.epa.gov/sites/production/files/2020-11/documents/2018_tables_and_figures_fnl_508.pdf.

EPA (2020c) Advancing Sustainable Materials Management: Facts and Figures 2016 and 2017. November 2019. Available online at: https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf.

EPA (2018) Advancing Sustainable Materials Management: Facts and Figures 2015. July 2018. Available online at: https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2016a) Industrial and Construction and Demolition Landfills. Available online at: https://www.epa.gov/landfills/industrial-and-construction-and-demolition-cd-landfills.

EPA (2016b) Advancing Sustainable Materials Management: Facts and Figures 2014. December 2016. Available online at: https://www.epa.gov/sites/production/files/2016-11/documents/2014_smm_tablesfigures_508.pdf.

EPA (2014) Advancing Sustainable Materials Management: Facts and Figures 2014. February 2014. Available online at: https://www.epa.gov/sites/production/files/2015-09/documents/2012_msw_dat_tbls.pdf.

EPA (2008) *Compilation of Air Pollution Emission Factors, Publication AP-42*, Draft Section 2.4 Municipal Solid Waste Landfills. October 2008.

EPA (1993) *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress*, U.S. Environmental Protection Agency, Office of Air and Radiation. Washington, D.C. EPA/430-R-93-003. April 1993.

EPA (1988) *National Survey of Solid Waste (Municipal) Landfill Facilities*, U.S. Environmental Protection Agency. Washington, D.C. EPA/530-SW-88-011. September 1988.

EREF (The Environmental Research & Education Foundation) (2016) Municipal Solid Waste Management in the United States: 2010 & 2013.

ERG (2023) Production Data Supplied by ERG for 1990-2022 for Pulp and Paper, Fruits and Vegetables, and Meat. September 7, 2021.

Food Waste Reduction Alliance (FWRA) (2016) Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Restaurants. A joint project by the Food Marketing Institute, the Grocery Manufacturers Association, and the National Restaurant Association. Available online at: https://foodwastealliance.org/wp-content/uploads/2020/05/FWRA-Food-Waste-Survey-2016-Report_Final.pdf.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Mancinelli, R. and C. McKay (1985) "Methane-Oxidizing Bacteria in Sanitary Landfills." *Proc. First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals*, Minneapolis, MN, 437-450. August.

RTI (2018) Methodological changes to the scale-up factor used to estimate emissions from municipal solid waste landfills in the Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). March 22, 2018.

RTI (2017) Methodological changes to the methane emissions from municipal solid waste landfills as reflected in the public review draft of the 1990-2015 Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). March 31, 2017.

RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA). January 14, 2011.

Waste Business Journal (WBJ) (2021) Directory of Waste Processing & Disposal Sites 2021.

WBJ (2016) Directory of Waste Processing & Disposal Sites 2016.

WBJ (2010) Directory of Waste Processing & Disposal Sites 2010.

Wastewater Treatment and Discharge

AF&PA (2022) "AF&PA Members Achieve Progress on Water Stewardship Goal for 2020." American Forest & Paper Association. Available online at: https://www.afandpa.org/statistics-resources/afpa-members-achieve-progress-water-stewardship-goal-2020. Accessed July 2022.

AF&PA (2020) "2020 AF&PA Sustainability Report: Advancing the sustainability of an essential industry." American Forest & Paper Association. Available online at: https://www.afandpa.org/sites/default/files/2021-07/2020_AF-PA-Sustainability-Report.pdf. Accessed June 2021.

AF&PA (2018) "2018 AF&PA Sustainability Report: Advancing U.S. Paper and Wood Products Industry Sustainability Performance." American Forest & Paper Association. Available online at: http://sustainability.afandpa.org/wp-content/uploads/2018/06/2018SustainabilityReport_PAGES.pdf. Accessed July 2019.

AF&PA (2016) "2016 AF&PA Sustainability Report: Advancing U.S. Paper and Wood Products Industry Sustainability Performance." American Forest & Paper Association.

AF&PA (2014) "2014 AF&PA Sustainability Report." American Forest & Paper Association.

Beecher et al. (2007) "A National Biosolids Regulation, Quality, End Use & Disposal Survey, Preliminary Report." Northeast Biosolids and Residuals Association, April 14, 2007. Available online at: https://static1.squarespace.com/static/54806478e4b0dc44e1698e88/t/5480c7a2e4b0787f2c73ad81/1417725858575/NtlBiosldsRpt-AppD-FINAL.pdf. Accessed August 2021.

Beer Institute (2011) Brewers Almanac. Available online at: http://www.beerinstitute.org/multimedia/brewers-almanac.

Benyahia, F., M. Abdulkarim, A. Embaby, and M. Rao. (2006) Refinery Wastewater Treatment: A true Technological Challenge. Presented at the Seventh Annual U.A.E. University Research Conference.

BIER (2021) 2021 Benchmarking Study Trends & Observations. Available online at https://www.bieroundtable.com/publication/2021-water-and-energy-use-benchmarking-study/. Accessed September 2023.

Brewers Association (2021) Statistics: Number of Breweries. Available online at: https://www.brewersassociation.org/statistics-and-data/national-beer-stats/. Accessed August 2021.

Brewers Association (2016a) 2015 Sustainability Benchmarking Report. Available online at: https://www.brewersassociation.org/best-practices/sustainability/sustainability-benchmarking-tools. Accessed March 2018.

Brewers Association (2016b) Wastewater Management Guidance Manual. Available online at: https://www.brewersassociation.org/educational-publications/wastewater-management-guidance-manual. Accessed September 2017.

Cabrera (2017) "Pulp Mill Wastewater: Characteristics and Treatment." Biological Wastewater Treatment and Resource Recovery. InTech. pp. 119–139.

CAST (1995) Council for Agricultural Science and Technology. Waste Management and Utilization in Food Production and Processing. U.S.A. October 1995. ISBN 1-887383-02-6. Available online at: https://www.cast-science.org/publication/waste-management-and-utilization-in-food-production-and-processing/.

Climate Action Reserve (CAR) (2011) Landfill Project Protocol V4.0, June 2011. Available online at: http://www.climateactionreserve.org/how/protocols/us-landfill/.

Cooper (2018) Email correspondence. Geoff Cooper, Renewable Fuels Association to Kara Edquist, ERG. "Wet Mill vs. Dry Mill Ethanol Production." May 18, 2018.

DOE (2013) U.S. Department of Energy Bioenergy Technologies Office. Biofuels Basics. Available online at: http://energy.gov/eere/bioenergy/biofuels-basics. Accessed September 2013.

Donovan (1996) Siting an Ethanol Plant in the Northeast. C.T. Donovan Associates, Inc. Report presented to Northeast Regional Biomass Program (NRBP). (April). Available online at: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.614.856&rep=rep1&type=pdf. Accessed October 2006.

EIA (2023) Energy Information Administration. U.S. Refinery and Blender Net Production of Crude Oil and Petroleum Products (Thousand Barrels). Available online at: https://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_m.htm. Accessed August 2023.

EPA (2019) Preliminary Effluent Guidelines Program Plan 14. EPA-821-R-19-005. Office of Water, U.S. Environmental Protection Agency. Washington, DC. October 2019. Available online at: https://www.epa.gov/sites/production/files/2019-10/documents/prelim-eg-plan-14_oct-2019.pdf. Accessed July 2020.

EPA (2013) U.S. Environmental Protection Agency. Report on the Performance of Secondary Treatment Technology. EPA-821-R-13-001. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. March 2013. Available online at: https://www.epa.gov/sites/production/files/2015-11/documents/npdes_secondary_treatment_report_march2013.pdf.

EPA (2012) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2012 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2012-report-and-data#access. Accessed February 2016.

EPA (2010) U.S. Environmental Protection Agency. Nutrient Control Design Manual. U.S. Environmental Protection Agency, Office of Research and Development. Washington, D.C. EPA600-R-10-100. Available online at: https://www.epa.gov/sites/default/files/2019-08/documents/nutrient_control_design_manual.pdf. Accessed December 2023.

EPA (2008) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2008 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2008-report-and-data. Accessed December 2015.

EPA (2004) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2004 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-report-congress-2004.

EPA (2000) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2000 - Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2000-report-and-data. Accessed July 2007.

EPA (1999) U.S. Environmental Protection Agency. Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. EPA530-R-99-009. September 1999.

EPA (1998) U.S. Environmental Protection Agency. "AP-42 Compilation of Air Pollutant Emission Factors." Chapter 2.4, Table 2.4-3, page 2.4-13. Available online at: https://www.epa.gov/sites/default/files/2020-10/documents/c02s04.pdf.

EPA (1997a) U.S. Environmental Protection Agency. Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. EPA-600/R-97-091. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency. Washington, D.C. September 1997.

EPA (1997b) U.S. Environmental Protection Agency. Supplemental Technical Development Document for Effluent Guidelines and Standards (Subparts B & E). EPA-821-R-97-011. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1997.

EPA (1996) U.S. Environmental Protection Agency. 1996 Clean Water Needs Survey Report to Congress. Assessment of Needs for Publicly Owned Wastewater Treatment Facilities, Correction of Combined Sewer Overflows, and Management of Storm Water and Nonpoint Source Pollution in the United States. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1993a) U.S. Environmental Protection Agency, "Anthropogenic Methane Emissions in the U.S.: Estimates for 1990, Report to Congress." Office of Air and Radiation, Washington, DC. April 1993.

EPA (1993b) U.S. Environmental Protection Agency. Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category. EPA-821-R-93-019. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1993.

EPA (1993c) Standards for the Use and Disposal of Sewage Sludge. 40 CFR Part 503.

EPA (1992) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 1992 – Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1982) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and standards for the Petroleum Refining. United States Environmental Protection Agency, Office of Water. EPA-440/1-82-014. Washington D.C. October 1982.

EPA (1975) U.S. Environmental Protection Agency. Development Document for Interim Final and Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Fruits, Vegetables, and Specialties Segment

of the Canned and Preserved Fruits and Vegetables Point Source Category. United States Environmental Protection Agency, Office of Water. EPA-440/1-75-046. Washington D.C. October 1975.

EPA (1974) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Apple, Citrus, and Potato Processing Segment of the Canned and Preserved Fruits and Vegetables Point Source Category. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. EPA-440/1-74-027-a. March 1974.

ERG (2023) Memorandum: Improvements to the 1990-2021 Wastewater Treatment and Discharge Greenhouse Gas Inventory. February 2023.

ERG (2021a) Revised Memorandum: Improvements to the 1990-2019 Wastewater Treatment and Discharge Greenhouse Gas Inventory. March 2021.

ERG (2021b) Draft Memorandum: Improvements to the 1990-2020 Wastewater Treatment and Discharge Greenhouse Gas Inventory. July 2021.

ERG (2021c) Draft Memorandum: Expert Judgement Documentation for the Wastewater Treatment and Discharge Greenhouse Gas Inventory Uncertainties, August 2021.

ERG (2019) Memorandum: Recommended Improvements to the 1990-2018 Wastewater Greenhouse Gas Inventory. August 2019.

ERG (2018a) Memorandum: Updates to Domestic Wastewater BOD Generation per Capita. August 2018.

ERG (2018b) Memorandum: Inclusion of Wastewater Treatment Emissions from Breweries. July 2018.

ERG (2016) Revised Memorandum: Recommended Improvements to the 1990-2015 Wastewater Greenhouse Gas Inventory. November 2016.

ERG (2013a) Memorandum: Revisions to Pulp and Paper Wastewater Inventory. October 2013.

ERG (2013b) Memorandum: Revisions to the Petroleum Refinery Wastewater Inventory. October 2013.

ERG (2008a) Memorandum: Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. 10 August 2008.

ERG (2008b) Memorandum: Estimation of Onsite Treatment at Industrial Facilities and Review of Wastewater Characterization Data. 15 April 2008.

ERG (2006a) Memorandum: Recommended Improvements to EPA's Wastewater Inventory for Industrial Wastewater. Prepared for Melissa Weitz, EPA. 11 August 2006.

ERG (2006b) Memorandum: Assessment of Greenhouse Gas Emissions from Wastewater Treatment of U.S. Ethanol Production Wastewaters. Prepared for Melissa Weitz, EPA. 10 October 2006.

FAO (2023a) FAOSTAT-Forestry Database. Available online at: http://www.fao.org/faostat/en/#data/FO. Accessed September 2023.

FAO (2023b) "Pulp and Paper Capacities Report." United States. From 1998 – 2003, 2000 – 2005, 2001 – 2006, 2002 – 2007, 2003 – 2008, 2010 – 2015, 2011 – 2016, 2012 – 2017, 2013 – 2018, 2014 – 2019, 2015 – 2020, 2016 – 2021, 2017 – 2022, 2018 – 2023, 2019 – 2024, 2020-2025, 2021-2026 reports. Available online at: http://www.fao.org/forestry/statistics/80571/en/. Accessed September 2023.

FAO (2022) FAOSTAT-Food Balance Sheets. Available online at: http://www.fao.org/faostat/en/#data/FBS. Accessed September 2023.

Foley et al. (2015) *N_2O and CH_4 Emission from Wastewater Collection and Treatment Systems: State of the Science Report and Technical Report*. GWRC Report Series. IWA Publishing, London, UK.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. (2004) Recommended Standards for Wastewater Facilities (Ten-State Standards).

Guisasola et al. (2008) Methane formation in sewer systems. *Water Research* 42(6–7): 1421-1430.

Instituto de Estadísticas de Puerto Rico (2021) Population of Puerto Rico from 1990-1999 from "Estimados anuales poblacionales de los municipios desde 1950." Accessed February 2021. Available online at: https://censo.estadisticas.pr/EstimadosPoblacionales.

IPCC (2022) Emission factor database: Emission Factor Detail (ID:625621). The Intergovernmental Panel on Climate Change. Available online at: https://www.ipcc-nggip.iges.or.jp/EFDB/ef_detail.php.

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [CalvoBuendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds)]. Switzerland.

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.)]. Published: IPCC, Switzerland.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kenari et. al (2010) An Investigation on the Nitrogen Content of a Petroleum Refinery Wastewater and its Removal by Biological Treatment. Journal of Environmental Health, Sciences, and Engineering. 7(1): 391-394.

Leverenz, H.L., G. Tchobanoglous, and J.L. Darby (2010) "Evaluation of Greenhouse Gas Emissions from Septic Systems." Water Environment Research Foundation. Alexandria, VA.

Lewis, A. (2019) Email correspondence. Ann Lewis, RFA to Kara Edquist, ERG. "Wet Mill vs Dry Mill Ethanol Production." August 20, 2019.

Malmberg, B. (2018) Draft Pulp and Paper Information for Revision of EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks, Waste Chapter. National Council for Air and Stream Improvement, Inc. Prepared for Rachel Schmeltz, EPA. June 13, 2018.

Merrick (1998) Wastewater Treatment Options for the Biomass-to-Ethanol Process. Report presented to National Renewable Energy Laboratory (NREL). Merrick & Company. Subcontract No. AXE-8-18020-01. October 22, 1998.

Metcalf & Eddy, Inc. (2014) Wastewater Engineering: Treatment and Resource Recovery, 5th ed. McGraw Hill Publishing.

Metcalf & Eddy, Inc. (2003) Wastewater Engineering: Treatment, Disposal and Reuse, 4th ed. McGraw Hill Publishing.

NEBRA (2022) "U.S. National Biosolids Data." Northeast Biosolids and Residuals Associations. Available online at: https://static1.squarespace.com/static/601837d1c67bcc4e1b11862f/t/62f4f5fbae32804dd9f51ef6/1660220925356/National_BiosolidsDataSummary_NBDP_20220811.pdf

Nemerow, N.L. and A. Dasgupta (1991) Industrial and Hazardous Waste Treatment. Van Nostrand Reinhold. NY. ISBN 0-442-31934-7.

NRBP (2001) Northeast Regional Biomass Program. An Ethanol Production Guidebook for Northeast States. Washington, D.C. (May 3).

Rendleman, C.M. and Shapouri, H. (2007) New Technologies in Ethanol Production. USDA Agricultural Economic Report Number 842.

RFA (2023a) Renewable Fuels Association. Annual U.S. Fuel Ethanol Production. Available online at: https://ethanolrfa.org/statistics/annual-ethanol-production. Accessed August 2023.

RFA (2023b) Renewable Fuels Association. Monthly Grain Use for U.S. Ethanol Production Report. Available online at: https://ethanolrfa.org/statistics/feedstock-use-co-product-output. Accessed August 2023.

Ruocco (2006a) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. "Capacity of Bio-Methanators (Dry Milling)." October 6, 2006.

Ruocco (2006b) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. "Capacity of Bio-Methanators (Wet Milling)." October 16, 2006.

Short et al. (2017) Dissolved Methane in the Influent of Three Australian Wastewater Treatment Plants Fed by Gravity Sewers. *Sci Total Environ* 599-600: 85-93.

Short et al. (2014) Municipal Gravity Sewers: an Unrecognised Source of Nitrous Oxide. *Sci Total Environ* 468-469: 211-218.

Stier, J. (2018) Personal communications between John Stier, Brewers Association Sustainability Mentor and Amie Aguiar, ERG. Multiple dates.

Sullivan (SCS Engineers) (2010) The Importance of Landfill Gas Capture and Utilization in the U.S. Presented to SWICS, April 6, 2010. Available online at: https://www.scsengineers.com/scs-white-papers/the-importance-of-landfill-gas-capture-and-utilization-in-the-u-s/.

Sullivan (SCS Engineers) (2007) Current MSW Industry Position and State of the Practice on Methane Destruction Efficiency in Flares, Turbines, and Engines. Presented to Solid Waste Industry for Climate Solutions (SWICS). July 2007. Available online at: https://www.scsengineers.com/wp-content/uploads/2015/03/Sullivan_LFG_Destruction_Efficiency_White_Paper.pdf.

TTB (2022) Alcohol and Tobacco Tax and Trade Bureau. Beer Statistics. Available online at: https://www.ttb.gov/beer/beer-stats.shtml. Accessed July 2021.

UNFCCC (2012) CDM Methodological tool, Project emissions from flaring (Version 02.0.0). EB 68 Report. Annex 15. Available online at: http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-06-v1.pdf/history_view.

U.S. Census Bureau (2023) International Database. Available online at: https://www.census.gov/data-tools/demo/idb/#/trends?YR_ANIM=2020&dashPages=DASH&FIPS_SINGLE=US&COUNTRY_YEAR=2022&menu=trendsViz&TREND_RANGE=1990,2022&TREND_STEP=5&TREND_ADD_YRS=&FIPS=AQ,GQ,CQ,RQ,VQ&measures=POP&CCODE=AS,GU,MP,PR,US,VI&CCODE_SINGLE=US&COUNTRY_YR_ANIM=2022. Accessed September 2023.

U.S. Census Bureau (2022) Annual Estimates of the Resident Population for the United States, Regions, States, District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2021. Available online at: https://www.census.gov/data/tables/time-series/demo/popest/2020s-national-total.html. Accessed July 2023.

U.S. Census Bureau (2021a) "American Housing Survey." Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, and 2009 reports. Table C-04-AO Plumbing, Water, and Sewage Disposal--All Occupied Units. From 2011, 2013, 2015, 2017, 2019 and 2021 reports. Available online at http://www.census.gov/programs-surveys/ahs/data.html. Accessed August 2023.

U.S. Census Bureau (2021b) Annual Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2010 to July 1, 2020. Available online at: https://www.census.gov/data/tables/time-series/demo/popest/2010s-state-total.html.

U.S. Census Bureau (2013) "American Housing Survey." Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, and 2009 reports. Table C-04-AO Plumbing, Water, and Sewage Disposal--All Occupied Units. From 2011, and 2013 reports. Available online at http://www.census.gov/programs-surveys/ahs/data.html. Accessed May 2020.

U.S. Census Bureau, Population Division (2011) Table 1. Intercensal Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2000 to July 1, 2010 (ST-EST00INT-01), Release Date: September 2011. Available online at: https://www2.census.gov/programs-surveys/popest/datasets/2000-2010/intercensal/state/st-est00int- alldata.csv.

U.S. Census Bureau, Population Division (2002) Table CO-EST2001-12-00 - Time Series of Intercensal State Population Estimates: April 1, 1990 to April 1, 2000.Available online at: https://www2.census.gov/programs-surveys/popest/tables/1990-2000/intercensal/st- co/co-est2001-12-00.pdf.

USDA (U.S. Department of Agriculture) (2023a) *Livestock Slaughter 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/r207tp32d/8p58qs65g/g445dv089/lsan0423.pdf

USDA (U.S. Department of Agriculture) (2023b) *Poultry Slaughter 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/pg15bd88s/m613p944x/ht24xx05j/pslaan23.pdf

USDA (U.S. Department of Agriculture) (2023c) *Vegetables 2022 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/02870v86p/hq37x121v/4b29ck28c/vegean23.pdf

USDA (U.S. Department of Agriculture) (2023d) *Noncitrus Fruits and Nuts 2022 Summary*. Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/zs25x846c/zk51wx21m/k356bk214/ncit0523.pdf

USDA (U.S. Department of Agriculture) (2022a) *Potato Annual 2021 Summary.* Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/fx719m44h/gb19gf71k/37721m72q/pots0922.pdf

USDA (U.S. Department of Agriculture) (2022b) *Citrus Fruits 2022 Summary*. Available online at: https://downloads.usda.library.cornell.edu/usda-esmis/files/j9602060k/pn89ff24k/zp38xm24q/cfrt0922.pdf

USDA (2015) U.S. Department of Agriculture. Economic Research Service. Nutrient Availability (food energy, nutrients, and dietary components). Washington D.C. Available online at: https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/food-availability-per-capita-data-system. Accessed September 2023.

U.S. Poultry (2006) Email correspondence. John Starkey, USPOULTRY to D. Bartram, ERG. 30 August 2006.

White and Johnson (2003) White, P.J. and Johnson, L.A. Editors. Corn: Chemistry and Technology. 2nd ed. AACC Monograph Series. American Association of Cereal Chemists. St. Paul, MN.

World Bank (1999) Pollution Prevention and Abatement Handbook 1998, Toward Cleaner Production. The International Bank for Reconstruction and Development/The WORLDBANK. 1818 H Street, N.W. Washington, DC. 20433, USA. ISBN 0-8213-3638-X.

Composting

BioCycle (2023) BioCycle Nationwide Survey: Full-Scale Food Waste Composting Infrastructure in the U.S. Prepared by N. Goldstein, P. Luu, and S. Motta. Available online at: https://www.biocycle.net/us-food-waste-composting-infrastructure/.

BioCycle (2018a) Organic Waste Bans and Recycling Laws to Tackle Food Waste. Prepared by E. Broad Lieb, K. Sandson, L. Macaluso, and C. Mansell. Available online at: https://www.biocycle.net/2018/09/11/organic-waste-bans-recycling-laws-tackle-food-waste/.

BioCycle (2018b) State Food Waste Recycling Data Collection, Reporting Analysis. Prepared by Nora Goldstein. Available online at: http://compostcolab.wpengine.com/wp-content/uploads/2018/11/State-Food-Waste-Recycling-Data-Collection-Reporting-Analysis.pdf.

BioCycle (2017) The State of Organics Recycling in the U.S. Prepared by Nora Goldstein. Available online at http://www.biocycle.net/17_10_06_1/0001/BioCycle_StateOfOrganicsUS.pdf.

BioCycle (2010) The State of Garbage in America. Prepared by Rob van Haaren, Nickolas Themelis and Nora Goldstein. Available online at http://www.biocycle.net/images/art/1010/bc101016_s.pdf.

Cornell Composting (1996) Monitoring Compost Moisture. Cornell Waste Management Institute. Available online at: http://compost.css.cornell.edu/monitor/monitormoisture.html.

Cornell Waste Management Institute (2007) The Science of Composting. Available online at http://cwmi.css.cornell.edu/chapter1.pdf.

EPA (2020) *Advancing Sustainable Materials Management: 2018 Tables and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf.

EPA (2018) *Advancing Sustainable Materials Management: 2015 Tables and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/production/files/2018-07/documents/smm_2015_tables_and_figures_07252018_fnl_508_0.pdf.

EPA (2016) *Advancing Sustainable Materials Management: Facts and Figures 2014*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/production/files/2016-11/documents/2014_smm_tablesfigures_508.pdf.

EPA (2014) *Municipal Solid Waste in the United States: 2012 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at https://www.epa.gov/sites/default/files/2015-09/documents/2012_msw_fs.pdf.

Harvard Law School and Center for EcoTechnology (CET) (2019) Bans and Beyond: Designing and Implementing Organic Waste Bans and Mandatory Organics Recycling Laws. Prepared by Katie Sandson and Emily Broad Leib, Harvard Law School Food Law and Policy Clinic, with input from Lorenzo Macaluso and Coryanne Mansell, Center for EcoTechnology (CET). Available online at https://wastedfood.cetonline.org/wp-content/uploads/2019/07/Harvard-Law-School-FLPC-Center-for-EcoTechnology-CET-Organic-Waste-Bans-Toolkit.pdf.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan. Available online at https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf.

Kijanka (2020) Email correspondence. Kenin Kijanka, EPA Region 2 to Rachel Schmeltz, EPA HQ. "Puerto Rico Composting Operations." November 13, 2020.

University of Maine (2016) Compost Report Interpretation Guide. Soil Testing Lab. Available online at: https://umaine.edu/soiltestinglab/wp-content/uploads/sites/227/2016/07/Compost-Report-Interpretation-Guide.pdf.

U.S. Census Bureau, Population Division (2023) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2022 (NST-EST2022-POP). Available online at https://www.census.gov/data/tables/time-series/demo/popest/2020s-state-total.html.

U.S. Census Bureau, Population Division (2022) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2020 to July 1, 2021 (NST-EST2021-POP). Available online at https://www.census.gov/data/datasets/time-series/demo/popest/2020s-national-total.html.

U.S. Census Bureau (2021) Table 1. Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2010 to July 1, 2019; April 1, 2020; and July 1, 2020 (NST-EST2020). Available online at https://www.census.gov/programs-surveys/popest/technical-documentation/research/evaluation-estimates/2020-evaluation-estimates/2010s-totals-national.html.

U.S. Composting Council (2022) State and City Organics Bans, as of June 2021. Accessed on September 29, 2022. Available at https://www.compostingcouncil.org/page/organicsbans.

U.S. Composting Council (2010) Yard Trimmings Bans: Impact and Support. Prepared by Stuart Buckner, Executive Director, U.S., Composting Council. Available online at https://cdn.ymaws.com/www.compostingcouncil.org/resource/resmgr/images/advocacy/Yard-Trimmings-Ban-Impacts-a.pdf.

Anaerobic Digestion at Biogas Facilities

Bronstein, Kate (2021) Expert Judgement Uncertainty of quantity of materials digested. RTI International, Solid Waste Management GHG Expert.

EPA (2023) Anaerobic Digestion Facilities Processing Food Waste in the United States (2019): Survey Results. April 2023 EPA 530-R-23-003. April 2023. Available online at https://www.epa.gov/system/files/documents/2023-04/Anaerobic_Digestion_Facilities_Processing_Food_Waste_in_the_United_States_2019_20230404_508.pdf.

EPA (2021) Anaerobic Digestion Facilities Processing Food Waste in the United States (2017 & 2018): Survey Results. January 2021 EPA/903/S-21/001. Available online at https://www.epa.gov/sites/default/files/2021-02/documents/2021_final_ad_report_feb_2_with_links.pdf.

EPA (2020) Types of Anaerobic Digesters: Common Ways to Describe Digesters. Available online at https://www.epa.gov/anaerobic-digestion/types-anaerobic-digesters.

EPA (2019) Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results. September 2019 EPA/903/S-19/001. Available online at https://www.epa.gov/sites/production/files/2018-08/documents/ad_data_report_final_508_compliant_no_password.pdf.

EPA (2018) Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results. May 2018 EPA/903/S-18/001. Available online at https://www.epa.gov/sites/production/files/2019-09/documents/ad_data_report_v10_-_508_comp_v1.pdf.

EPA (2016) Frequently Asked Questions About Anaerobic Digestion. Available online at https://www.epa.gov/anaerobic-digestion/frequent-questions-about-anaerobic-digestion#codigestion.

EPA (1993) Anthropogenic Methane Emissions in the U.S.: Estimates for 1990, Report to Congress. Office of Air and Radiation, Washington, DC. April 1993.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan. Available online at https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf.

Water Environment Federation (WEF) (2012) What Every Operator Should Know about Anaerobic Digestion. Available online at https://www.wef.org/globalassets/assets-wef/direct-download-library/public/operator-essentials/wet-operator-essentials---anaerobic-digestion---dec12.pdf.

Waste Incineration

RTI (2009) Hospital/Medical/Infectious Waste Incinerators: Summary of Requirements for Revised or New Section 111(d)/129 State Plans Following Amendments to the Emission Guidelines. Available online at https://nepis.epa.gov/Exe/ZyPDF.cgi/P1009ZW6.PDF?Dockey=P1009ZW6.PDF.

Waste Sources of Precursor Greenhouse Gas Emissions

EPA (2023a) "Criteria pollutants National Tier 1 for 1970 - 2023." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2024. Available online at: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

EPA (2023b) "2020 National Emissions Inventory Technical Support Document: Introduction." Office of Air Quality Planning and Standards, March 2023. Available online at: https://www.epa.gov/system/files/documents/2023-01/NEI2020_TSD_Section1_Introduction.pdf.

Recalculations and Improvements

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland. IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Air conditioner
ACC	American Chemistry Council
AEDT	FAA Aviation Environmental Design Tool
AEO	Annual Energy Outlook
AER	All-electric range
AF&PA	American Forest and Paper Association
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFOLU	Agriculture, Forestry, and Other Land Use
AFV	Alternative fuel vehicle
AGA	American Gas Association
AGR	Acid gas removal
AHEF	Atmospheric and Health Effects Framework
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AIM Act	American Innovation and Manufacturing Act
AISI	American Iron and Steel Institute
ALU	Agriculture and Land Use
ANGA	American Natural Gas Alliance
ANL	Argonne National Laboratory
APC	American Plastics Council
API	American Petroleum Institute
APTA	American Public Transportation Association
AR4	IPCC *Fourth Assessment Report*
AR5	IPCC *Fifth Assessment Report*
AR6	IPCC *Sixth Assessment Report*
ARI	Advanced Resources International
ARMA	Autoregressive moving-average
ARMS	Agricultural Resource Management Surveys
ASAE	American Society of Agricultural Engineers
ASLRRA	American Short-line and Regional Railroad Association
ASR	Annual Statistical Report
ASTM	American Society for Testing and Materials
AZR	American Zinc Recycling
BCEF	Biomass conversion and expansion factors
BEA	Bureau of Economic Analysis, U.S. Department of Commerce
BIER	Beverage Industry Environmental Roundtable
BLM	Bureau of Land Management
BoC	Bureau of Census
BOD	Biological oxygen demand
BOD5	Biochemical oxygen demand over a 5-day period
BOEM	Bureau of Ocean Energy Management
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOF	Basic oxygen furnace
BRS	Biennial Reporting System
BSEE	Bureau of Safety and Environmental Enforcement
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C	Carbon
C&D	Construction and demolition waste
C&EN	Chemical and Engineering News
CAAA	Clean Air Act Amendments of 1990
CAFOS	Concentrated Animal Feeding Operations
CAGR	Compound Annual Growth Rate
CaO	Calcium oxide
CAPP	Canadian Association of Petroleum Producers
CARB	California Air Resources Board
CBI	Confidential business information
C-CAP	Coastal Change Analysis Program
CDAT	Chemical Data Access Tool
CEAP	USDA-NRCS Conservation Effects Assessment Program
CEFM	Cattle Enteric Fermentation Model
CEMS	Continuous emission monitoring system
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CH_4	Methane
CHAPA	California Health and Productivity Audit
CHP	Combined heat and power
CI	Confidence interval
CIGRE	International Council on Large Electric Systems
CKD	Cement kiln dust
CLE	Crown Light Exposure
CMA	Chemical Manufacturer's Association
CMM	Coal mine methane
CMOP	Coalbed Methane Outreach Program
CMR	Chemical Market Reporter
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COGCC	Colorado Oil and Gas Conservation Commission
CONUS	Continental United States
CRF	Common Reporting Format
CRM	Component ratio method
CRP	Conservation Reserve Program
CSRA	Carbon Sequestration Rural Appraisals
CTIC	Conservation Technology Information Center
CVD	Chemical vapor deposition
CWNS	Clean Watershed Needs Survey
d.b.h	Diameter breast height
DE	Digestible energy

DESC	Defense Energy Support Center-DoD's Defense Logistics Agency
DFAMS	Defense Fuels Automated Management System
DGGS	Division of Geological & Geophysical Surveys
DHS	Department of Homeland Security
DLA	DoD's Defense Logistics Agency
DM	Dry matter
DOC	Degradable organic carbon
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOM	Dead organic matter
DOT	U.S. Department of Transportation
DRE	Destruction or removal efficiencies
DRI	Direct Reduced Iron
EAF	Electric arc furnace
EDB	Aircraft Engine Emissions Databank
EDF	Environmental Defense Fund
EER	Energy economy ratio
EF	Emission factor
EFMA	European Fertilizer Manufacturers Association
EJ	Exajoule
EGR	Exhaust gas recirculation
EGU	Electric generating unit
EIA	Energy Information Administration, U.S. Department of Energy
EIIP	Emissions Inventory Improvement Program
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EREF	Environment Research & Education Foundation
ERS	Economic Research Service
ETMS	Enhanced Traffic Management System
EV	Electric vehicle
EVI	Enhanced Vegetation Index
FAA	Federal Aviation Administration
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization database
FAS	Fuels Automated System
FCCC	Framework Convention on Climate Change
FEB	Fiber Economics Bureau
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FGD	Flue gas desulfurization
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FIADB	Forest Inventory and Analysis Database
FIPR	Florida Institute of Phosphate Research
FOD	First order decay
FOEN	Federal Office for the Environment
FOKS	Fuel Oil and Kerosene Sales
FQSV	First-quarter of silicon volume
FSA	Farm Service Agency
FTA	Federal Transit Authority
FTP	Federal Test Procedure
g	Gram
G&B	Gathering and boosting
GaAs	Gallium arsenide
GCV	Gross calorific value
GDP	Gross domestic product
GEI	Gulfwide Emissions Inventory
GHG	Greenhouse gas
GHGRP	EPA's Greenhouse Gas Reporting Program
GIS	Geographic Information Systems
GJ	Gigajoule
GOADS	Gulf Offshore Activity Data System
GOM	Gulf of Mexico
GPG	Good Practice Guidance
GRI	Gas Research Institute
GSAM	Gas Systems Analysis Model
GTI	Gas Technology Institute
GWP	Global warming potential
ha	Hectare
HBFC	Hydrobromofluorocarbon
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HDDV	Heavy duty diesel vehicle
HDGV	Heavy duty gas vehicle
HDPE	High density polyethylene
HF	Hydraulically fractured
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HFE	Hydrofluoroether
HHV	Higher Heating Value
HMA	Hot Mix Asphalt
HMIWI	Hospital/medical/infectious waste incinerator
HTF	Heat Transfer Fluid
HTS	Harmonized Tariff Schedule
HVAE	High Voltage Anode Effects
HWP	Harvested wood product
IBF	International bunker fuels
IC	Integrated Circuit
ICAO	International Civil Aviation Organization
ICBA	International Carbon Black Association
ICE	Internal combustion engine
ICR	Information Collection Request
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IGES	Institute of Global Environmental Strategies
IISRP	International Institute of Synthetic Rubber Products
ILENR	Illinois Department of Energy and Natural Resources
IMO	International Maritime Organization
IPAA	Independent Petroleum Association of America
IPCC	Intergovernmental Panel on Climate Change

IPPU	Industrial Processes and Product Use
ISO	International Organization for Standardization
ITC	U.S. International Trade Commission
ITRS	International Technology Roadmap for Semiconductors
JWR	Jim Walters Resources
KCA	Key category analysis
kg	Kilogram
kt	Kiloton
kWh	Kilowatt hour
LDPE	Low density polyethylene
LDT	Light-duty truck
LDV	Light-duty vehicle
LEV	Low emission vehicles
LFG	Landfill gas
LFGTE	Landfill gas-to-energy
LHV	Lower Heating Value
LKD	Lime kiln dust
LLDPE	Linear low density polyethylene
LMOP	EPA's Landfill Methane Outreach Program
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas(es)
LTO	Landing and take-off
LULUCF	Land Use, Land-Use Change, and Forestry
LVAE	Low Voltage Anode Effects
M&R	Metering and regulating
MARPOL	International Convention for the Prevention of Pollution from Ships
MC	Motorcycle
MCF	Methane conversion factor
MCL	Maximum Contaminant Levels
MCFD	Thousand cubic feet per day
MDI	Metered dose inhalers
MDP	Management and design practices
MECS	EIA Manufacturer's Energy Consumption Survey
MEMS	Micro-electromechanical systems
MER	Monthly Energy Review
MGO	Marine gas oil
MgO	Magnesium oxide
MJ	Megajoule
MLRA	Major Land Resource Area
mm	Millimeter
MMBtu	Million British thermal units
MMCF	Million cubic feet
MMCFD	Million cubic feet per day
MMS	Minerals Management Service
MMT	Million metric tons
MMTCE	Million metric tons carbon equivalent
MMT CO_2 Eq.	Million metric tons carbon dioxide equivalent
MODIS	Moderate Resolution Imaging Spectroradiometer
MoU	Memorandum of Understanding
MOVES	U.S. EPA's Motor Vehicle Emission Simulator model
MPG	Miles per gallon
MRLC	Multi-Resolution Land Characteristics Consortium
MRV	Monitoring, reporting, and verification
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MT	Metric ton
MTBE	Methyl Tertiary Butyl Ether
MTBS	Monitoring Trends in Burn Severity
MVAC	Motor vehicle air conditioning
MY	Model year
N_2O	Nitrous oxide
NA	Not applicable; Not available
NACWA	National Association of Clean Water Agencies
NAFTA	North American Free Trade Agreement
NAHMS	National Animal Health Monitoring System
NAICS	North American Industry Classification System
NAPAP	National Acid Precipitation and Assessment Program
NARR	North American Regional Reanalysis Product
NAS	National Academies of Sciences, Engineering, and Medicine
NASA	National Aeronautics and Space Administration
NASF	National Association of State Foresters
NASS	USDA's National Agriculture Statistics Service
NC	No change
NCASI	National Council of Air and Stream Improvement
NCV	Net calorific value
ND	No data
NE	Not estimated
NEH	National Engineering Handbook
NEI	National Emissions Inventory
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
NESHAP	National Emission Standards for Hazardous Air Pollutants
NEU	Non-Energy Use
NEV	Neighborhood Electric Vehicle
NF_3	Nitrogen trifluoride
NFI	National forest inventory
NGL	Natural gas liquids
NGO	Non-Governmental Organization
NID	National inventory of Dams
NIR	National Inventory Report
NLA	National Lime Association
NLCD	National Land Cover Dataset
NMOC	Non-methane organic compounds
NMVOC	Non-methane volatile organic compound
NMOG	Non-methane organic gas
NO	Not occurring
NO_2	Nitrogen dioxide

NO_x	Nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
NOF	Not on feed
NPDES	National Pollutant Discharge Elimination System
NPP	Net primary productivity
NPRA	National Petroleum and Refiners Association
NRBP	Northeast Regional Biomass Program
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
NRI	National Resources Inventory
NSCEP	National Service Center for Environmental Publications
NSCR	Non-selective catalytic reduction
NSPS	New source performance standards
NWS	National Weather Service
OAG	Official Airline Guide
OAP	EPA Office of Atmospheric Programs
OAQPS	EPA Office of Air Quality Planning and Standards
ODP	Ozone depleting potential
ODS	Ozone depleting substances
OECD	Organization of Economic Co-operation and Development
OEM	Original equipment manufacturers
OGJ	Oil & Gas Journal
OGOR	Oil and Gas Operations Reports
OH	Hydroxyl radical
OPEC	Organization of Petroleum-Exporting Countries
OMS	EPA Office of Mobile Sources
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTA	Office of Technology Assessment
OTAQ	EPA Office of Transportation and Air Quality
OVS	Offset verification statement
PADUS	Protected Areas Database of the United States
PAH	Polycyclic aromatic hydrocarbons
PCA	Portland Cement Association
PCC	Precipitate calcium carbonate
PDF	Probability Density Function
PECVD	Plasma enhanced chemical vapor deposition
PET	Polyethylene terephthalate
PET	Potential evapotranspiration
PEVM	PFC Emissions Vintage Model
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
PHEV	Plug-in hybrid vehicles
PHMSA	Pipeline and Hazardous Materials Safety Administration
PI	Productivity index
PLS	Pregnant liquor solution
PM	Particulate matter
POTW	Publicly Owned Treatment Works
ppbv	Parts per billion (10^9) by volume
ppm	Parts per million
ppmv	Parts per million (10^6) by volume
pptv	Parts per trillion (10^{12}) by volume
PRCI	Pipeline Research Council International
PRP	Pasture/Range/Paddock
PS	Polystyrene
PSU	Primary Sample Unit
PU	Polyurethane
PVC	Polyvinyl chloride
PV	Photovoltaic
QA/QC	Quality Assurance and Quality Control
QBtu	Quadrillion Btu
R&D	Research and Development
RECs	Reduced Emissions Completions
RCRA	Resource Conservation and Recovery Act
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RMA	Rubber Manufacturers' Association
RPA	Resources Planning Act
RTO	Regression-through-the-origin
SAE	Society of Automotive Engineers
SAGE	System for assessing Aviation's Global Emissions
SAIC	Science Applications International Corporation
SAN	Styrene Acrylonitrile
SAR	IPCC Second Assessment Report
SCR	Selective catalytic reduction
SCSE	South central and southeastern coastal
SDR	Steel dust recycling
SEC	Securities and Exchange Commission
SEMI	Semiconductor Equipment and Materials Industry
SF_6	Sulfur hexafluoride
SIA	Semiconductor Industry Association
SiC	Silicon carbide
SICAS	Semiconductor International Capacity Statistics
SNAP	Significant New Alternative Policy Program
SNG	Synthetic natural gas
SO_2	Sulfur dioxide
SOC	Soil Organic Carbon
SOG	State of Garbage survey
SOHIO	Standard Oil Company of Ohio
SSURGO	Soil Survey Geographic Database
STMC	Scrap Tire Management Council
SULEV	Super Ultra Low Emissions Vehicle
SWANA	Solid Waste Association of North America
SWDS	Solid waste disposal sites
SWICS	Solid Waste Industry for Climate Solutions
TA	Treated anaerobically (wastewater)
TAM	Typical animal mass
TAME	Tertiary amyl methyl ether
TAR	IPCC Third Assessment Report
TBtu	Trillion Btu
TDN	Total digestible nutrients
TEDB	Transportation Energy Data Book

TFI	The Fertilizer Institute
TIGER	Topologically Integrated Geographic Encoding and Referencing survey
TJ	Terajoule
TLEV	Traditional low emissions vehicle
TMLA	Total Manufactured Layer Area
TOW	Total organics in wastewater
TPO	Timber Product Output
TRI	Toxic Release Inventory
TSDF	Hazardous waste treatment, storage, and disposal facility
TTB	Tax and Trade Bureau
TVA	Tennessee Valley Authority
UAN	Urea ammonium nitrate
UDI	Utility Data Institute
UFORE	U.S. Forest Service's Urban Forest Effects model
UG	Underground (coal mining)
U.S.	United States
U.S. ITC	United States International Trade Commission
UEP	United Egg Producers
ULEV	Ultra low emission vehicle
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAA	U.S. Aluminum Association
USAF	United States Air Force
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
USITC	U.S. International Trade Commission
VAIP	EPA's Voluntary Aluminum Industrial Partnership
VAM	Ventilation air methane
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	Volatile organic compounds
VS	Volatile solids
WBJ	Waste Business Journal
WEF	Water Environment Federation
WERF	Water Environment Research Federation
WFF	World Fab Forecast (previously WFW, World Fab Watch)
WGC	World Gas Conference
WIP	Waste-in-place
WMO	World Meteorological Organization
WMS	Waste management systems
WRRF	Water resource recovery facilities
WTE	Waste-to-energy
WW	Wastewater
WWTP	Wastewater treatment plant
ZEVs	Zero emissions vehicles