EPA 430-R-15-004

Inventory of U.S. Greenhouse Gas Emissions and Sinks:

1990 – 2013

APRIL 15, 2015

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All data tables of this document are available for the full time series 1990 through 2013, inclusive, at the internet site mentioned above.

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For more information regarding climate change and greenhouse gas emissions, see the EPA web site at <http://www.epa.gov/climatechange>.

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Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC). Under decision 3/CP.5 of the UNFCCC Conference of the Parties, national inventories for UNFCCC Annex I parties should be provided to the UNFCCC Secretariat 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 availability of the draft document is announced via Federal Register Notice and is posted on the EPA web site. Copies are also mailed upon request. The public comment period is generally limited to 30 days; however, comments received after the closure of the public comment period are accepted and considered for the next edition of this annual report.

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Executive Summary

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

In 1992, the United States signed and ratified the UNFCCC. As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2]

Parties to the Convention, by ratifying, "shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[3] The United States views this report as an opportunity to fulfill these commitments.

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2013. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC Parties, the estimates presented here were calculated using methodologies consistent with those recommended in the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The structure of this report is consistent with the UNFCCC guidelines for inventory reporting.[4]

Box ES- 1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions 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.[5] Additionally, the calculated emissions

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[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] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://unfccc.int>.

[3] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12). Subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. See <http://unfccc.int>.

[4] See < http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf >.

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

and sinks in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[6] The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases (GHG) from large GHG emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP). 40 CFR part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons.[7] Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. The GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective methodological and planned improvements sections in this report's chapters, EPA is using the data, as applicable, to improve the national estimates presented in this Inventory.

ES.1. Background Information

Greenhouse gases trap heat and make the planet warmer. The most important greenhouse gases directly emitted by humans include CO_2, CH_4, N_2O, and several other fluorine-containing halogenated substances. Although the direct greenhouse gases 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 2013, concentrations of these greenhouse gases have increased globally by 43, 152, and 20 percent, respectively (IPCC 2007 and NOAA/ESRL 2015). This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States.

Global Warming Potentials

Gases in the atmosphere can contribute to climate change both directly and indirectly. Direct effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations of the substance produce other greenhouse gases, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects atmospheric processes that alter the radiative balance of the earth (e.g., affect cloud formation or albedo).[8] The IPCC developed the Global Warming Potential (GWP) concept to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas.

The GWP of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC 2013). Direct radiative effects occur when the gas itself is a greenhouse gas. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[9,10] All gases in this

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[6] See < http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php >.

[7] See <http://www.epa.gov/climatechange/emissions/ghgrulemaking.html> and <http://ghgdata.epa.gov/ghgp/main.do>.

[8] Albedo is a measure of the Earth's reflectivity, and is defined as the fraction of the total solar radiation incident on a body that is reflected by it.

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

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

Executive Summary are presented in units of MMT CO_2 Eq. Emissions by gas in unweighted mass tons are provided in the Trends chapter of this report.

Revised UNFCCC reporting guidelines for national inventories now require the use of GWP values from the *IPCC Fourth Assessment Report (AR4)* (IPCC 2007).[11] Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using AR4 GWP values, which have replaced the previously required use of SAR GWP values in the U.S. Inventory. All estimates are provided throughout the report in both CO_2 equivalents and unweighted units. A comparison of emission values using the AR4 GWP values versus the *IPCC Second Assessment Report (SAR)* (IPCC 1996), *IPCC Third Assessment Report (TAR)* (IPCC 2001), and the *IPCC Fifth Assessment Report (AR5)* (IPCC 2013) GWP values can be found in Chapter 1 and, in more detail, in Annex 6.1 of this report. The GWP values used in this report are listed below in Table ES-1. The use of IPCC AR4 GWP values in this and in future year inventories will apply across the entire time series of the Inventory (i.e., from 1990 to 2013 in this year's report).

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

Gas	GWP
CO_2	1
CH_4[a]	25
N_2O	298
HFC-23	14,800
HFC-32	675
HFC-125	3,500
HFC-134a	1,430
HFC-143a	4,470
HFC-152a	124
HFC-227ea	3,220
HFC-236fa	9,810
HFC-4310mee	1,640
CF_4	7,390
C_2F_6	12,200
C_4F_{10}	8,860
C_6F_{14}	9,300
SF_6	22,800
NF_3	17,200

Source: IPCC (2007)

[a] The CH_4 GWP 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.

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[11] See < http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf >.

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

In 2013, total U.S. greenhouse gas emissions were 6,673.0 MMT, or million metric tons, CO_2 Eq. Total U.S. emissions have increased by 5.9 percent from 1990 to 2013, and emissions increased from 2012 to 2013 by 2.0 percent (127.9 MMT CO_2 Eq.). The increase from 2012 to 2013 was due to an increase in the carbon intensity of fuels consumed to generate electricity due to an increase in coal consumption, with decreased natural gas consumption. Additionally, relatively cool winter conditions led to an increase in fuels for the residential and commercial sectors for heating. In 2013 there also was an increase in industrial production across multiple sectors resulting in increases in industrial sector emissions. Lastly, transportation emissions increased as a result of a small increase in vehicle miles traveled (VMT) and fuel use across on-road transportation modes. Since 1990, U.S. emissions have increased at an average annual rate of 0.3 percent. Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute change since 1990.

Table ES-2 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2013.

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

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

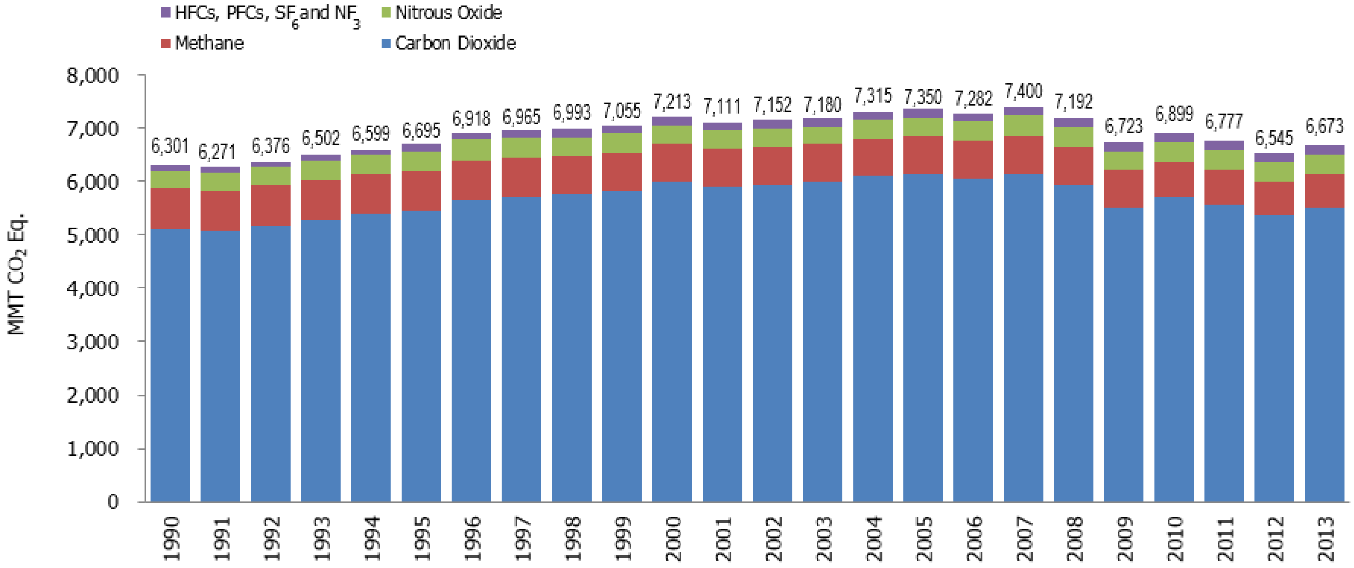


Figure ES-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

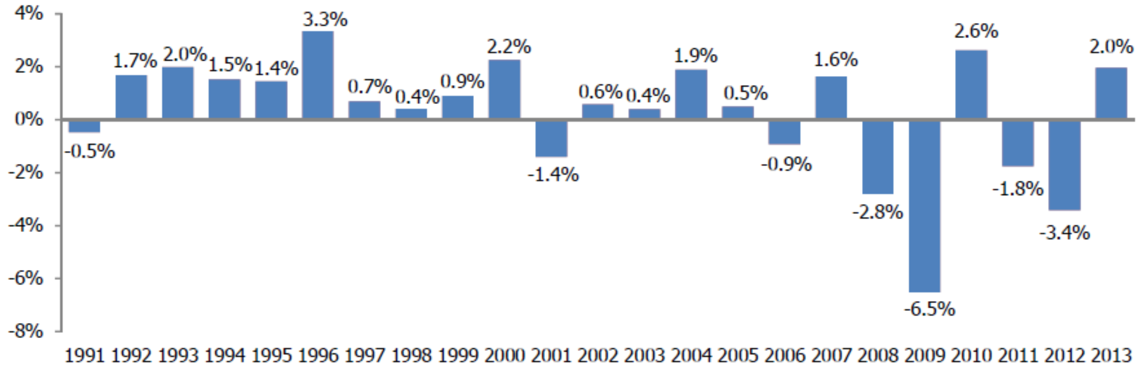


Figure ES-3: Annual Greenhouse Gas Emissions Relative to 1990 (1990=0)

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

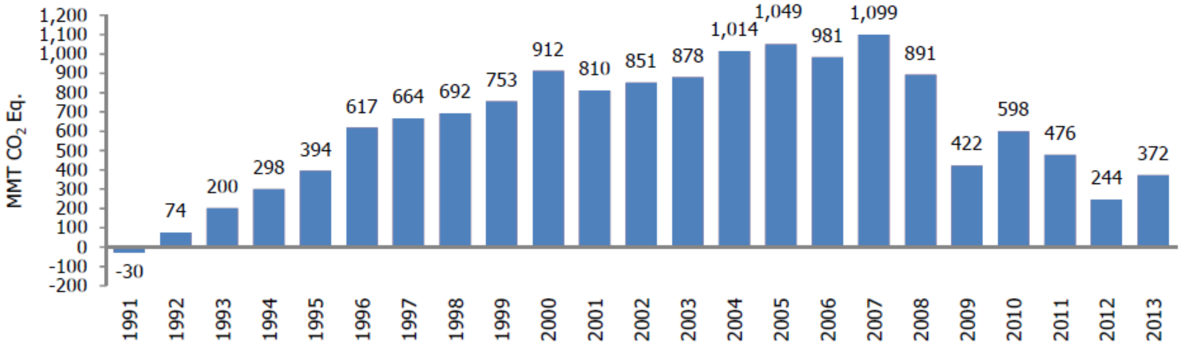


Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**5,123.7**	**6,134.0**	**5,500.6**	**5,704.5**	**5,568.9**	**5,358.3**	**5,505.2**
Fossil Fuel Combustion	4,740.7	5,747.7	5,197.1	5,367.1	5,231.3	5,026.0	5,157.7
Electricity Generation	1,820.8	2,400.9	2,145.7	2,258.4	2,157.7	2,022.2	2,039.8
Transportation	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4
Industrial	842.5	827.8	727.7	775.7	774.1	784.2	817.3
Residential	338.3	357.8	336.4	334.7	327.2	283.1	329.6
Commercial	217.4	223.5	223.5	220.2	221.0	197.1	220.7
U.S. Territories	27.9	49.9	43.5	46.2	39.8	38.6	32.0
Non-Energy Use of Fuels	117.7	138.9	106.0	114.6	108.4	104.9	119.8
Iron and Steel Production & Metallurgical Coke Production	99.8	66.7	43.0	55.7	60.0	54.3	52.3
Natural Gas Systems	37.6	30.0	32.2	32.3	35.6	34.8	37.8
Cement Production	33.3	45.9	29.4	31.3	32.0	35.1	36.1
Petrochemical Production	21.6	28.1	23.7	27.4	26.4	26.5	26.5
Lime Production	11.7	14.6	11.4	13.4	14.0	13.7	14.1
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2
Incineration of Waste	8.0	12.5	11.3	11.0	10.5	10.4	10.1
Petroleum Systems	4.4	4.9	4.7	4.2	4.5	5.1	6.0
Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.4	4.7	4.0	4.4	4.7

Other Process Uses of Carbonates	4.9	6.3	7.6	9.6	9.3	8.0	4.4
Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Aluminum Production	6.8	4.1	3.0	2.7	3.3	3.4	3.3
Soda Ash Production and Consumption	2.7	2.9	2.5	2.6	2.6	2.7	2.7
Ferroalloy Production	2.2	1.4	1.5	1.7	1.7	1.9	1.8
Titanium Dioxide Production	1.2	1.8	1.6	1.8	1.7	1.5	1.6
Zinc Production	0.6	1.0	0.9	1.2	1.3	1.5	1.4
Phosphoric Acid Production	1.6	1.4	1.0	1.1	1.2	1.1	1.2
Glass Production	1.5	1.9	1.0	1.5	1.3	1.2	1.2
Carbon Dioxide Consumption	1.5	1.4	1.8	1.2	0.8	0.8	0.9
Peatlands Remaining Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.1	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(775.8)*	*(911.9)*	*(870.9)*	*(871.6)*	*(881.0)*	*(880.4)*	*(881.7)*
Wood Biomass and Ethanol Consumption[b]	*219.4*	*229.8*	*250.5*	*265.1*	*268.1*	*267.7*	*283.3*
International Bunker Fuels[c]	*103.5*	*113.1*	*106.4*	*117.0*	*111.7*	*105.8*	*99.8*
CH_4	**745.5**	**707.8**	**709.5**	**667.2**	**660.9**	**647.6**	**636.3**
Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5
Natural Gas Systems	179.1	176.3	168.0	159.6	159.3	154.4	157.4
Landfills	186.2	165.5	158.1	121.8	121.3	115.3	114.6
Coal Mining	96.5	64.1	79.9	82.3	71.2	66.5	64.6
Manure Management	37.2	56.3	59.7	60.9	61.4	63.7	61.4
Petroleum Systems	31.5	23.5	21.5	21.3	22.0	23.3	25.2
Wastewater Treatment	15.7	15.9	15.6	15.5	15.3	15.2	15.0
Rice Cultivation	9.2	8.9	9.4	11.1	8.5	9.3	8.3
Stationary Combustion	8.5	7.4	7.4	7.1	7.1	6.6	8.0
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.6	6.4	6.2	6.2
Forest Fires	2.5	8.3	5.8	4.7	14.6	15.7	5.8
Mobile Combustion	5.6	3.0	2.3	2.3	2.3	2.2	2.1
Composting	0.4	1.9	1.9	1.8	1.9	1.9	2.0
Iron and Steel Production & Metallurgical Coke Production	1.1	0.9	0.4	0.6	0.7	0.7	0.7
Field Burning of Agricultural Residues	0.3	0.2	0.3	0.3	0.3	0.3	0.3
Petrochemical Production	0.2	0.1	+	0.1	+	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[c]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**329.9**	**355.9**	**356.1**	**360.1**	**371.9**	**365.6**	**355.2**
Agricultural Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7
Stationary Combustion	11.9	20.2	20.4	22.2	21.3	21.4	22.9
Mobile Combustion	41.2	38.1	24.6	23.7	22.5	20.2	18.4
Manure Management	13.8	16.4	17.0	17.1	17.3	17.3	17.3
Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7
Wastewater Treatment	3.4	4.3	4.6	4.7	4.8	4.9	4.9
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Adipic Acid Production	15.2	7.1	2.7	4.2	10.2	5.5	4.0
Forest Fires	1.7	5.5	3.8	3.1	9.6	10.3	3.8

Settlement Soils	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Composting	0.3	1.7	1.7	1.6	1.7	1.7	1.8
Forest Soils	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Semiconductor Manufacture	+	0.1	0.1	0.1	0.2	0.2	0.2
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*0.9*	*1.0*	*1.0*	*0.9*	*0.9*
HFCs	**46.6**	**131.4**	**142.9**	**152.6**	**157.4**	**159.2**	**163.0**
Substitution of Ozone Depleting Substances[d]	0.3	111.1	136.0	144.4	148.4	153.5	158.6
HCFC-22 Production	46.1	20.0	6.8	8.0	8.8	5.5	4.1
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	0.0	0.0	+	+	+	+	0.1
PFCs	**24.3**	**6.6**	**3.9**	**4.4**	**6.9**	**6.0**	**5.8**
Aluminum Production	21.5	3.4	1.9	1.9	3.5	2.9	3.0
Semiconductor Manufacture	2.8	3.2	2.0	2.6	3.4	3.0	2.9
SF_6	**31.1**	**14.0**	**9.3**	**9.5**	**10.0**	**7.7**	**6.9**
Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1
Magnesium Production and Processing	5.2	2.7	1.6	2.1	2.8	1.6	1.4
Semiconductor Manufacture	0.5	0.7	0.3	0.4	0.4	0.4	0.4
NF_3	**+**	**0.5**	**0.4**	**0.5**	**0.7**	**0.6**	**0.6**
Semiconductor Manufacture	+	0.5	0.4	0.5	0.7	0.6	0.6
Total Emissions	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**
Total Sinks[a]	**(775.8)**	**(911.9)**	**(870.9)**	**(871.6)**	**(881.0)**	**(880.4)**	**(881.7)**
Net Emissions (Sources and Sinks)	**5,525.2**	**6,438.3**	**5,851.9**	**6,027.2**	**5,895.6**	**5,664.7**	**5,791.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Parentheses indicate negative values or sequestration. Sinks (i.e., CO_2 removals) are only included in the Net Emissions total. Refer to Table ES-5 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

[b] Emissions from Wood Biomass and Ethanol 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 Land Use, Land-Use Change, and Forestry.

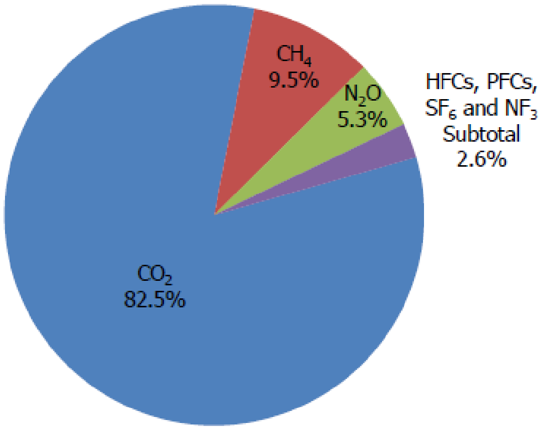
[c] Emissions from International Bunker Fuels are not included in totals.

[d] Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2013. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing approximately 82.5 percent of total greenhouse gas emissions. The largest source of CO_2, and of overall greenhouse gas emissions, was fossil fuel combustion. CH_4 emissions, which have decreased by 14.6 percent since 1990, resulted primarily from enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of wastes in landfills. Agricultural soil management, manure management, mobile source fuel combustion and stationary fuel combustion were the major sources of N_2O emissions. Ozone depleting substance substitute emissions and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate HFC emissions. PFC emissions resulted as a byproduct of primary aluminum production and from semiconductor manufacturing, while electrical transmission and distribution systems accounted for most SF_6 emissions.

Figure ES-4: 2013 Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)



Overall, from 1990 to 2013, total emissions of CO_2 increased by 381.5 MMT CO_2 Eq. (7.4 percent), while total emissions of CH_4 decreased by 109.2 MMT CO_2 Eq. (14.6 percent), and N_2O increased by 25.3 MMT CO_2 Eq. (7.7 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, SF_6 and NF_3 rose by 74.3 MMT CO_2 Eq. (72.9 percent). From 1990 to 2013, HFCs increased by 116.4 MMT CO_2 Eq. (249.8 percent), PFCs decreased by 18.4 MMT CO_2 Eq. (76.0 percent), SF_6 decreased by 24.1 MMT CO_2 Eq. (77.7 percent), and NF_3 increased by 0.5 MMT CO_2 Eq. (1,070.1 percent). 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 these gases have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests, trees in urban areas, agricultural soils, and landfilled yard trimmings and food scraps, which, in aggregate, offset 13.2 percent of total emissions in 2013. The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

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, carbon fluxes among these various reservoirs are roughly balanced.[12] Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen approximately 43 percent (IPCC 2007 and NOAA/ESRL 2015), principally due to the combustion of fossil fuels. Within the United States, fossil fuel combustion accounted for 93.7 percent of CO_2 emissions in 2013. Globally, approximately 32,310 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2012, of which the United States accounted for about 16 percent.[13] Changes in land use and forestry practices can also emit CO_2 (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for CO_2 (e.g., through net additions to forest biomass). Although fossil fuel combustion is the greatest source of CO_2 emissions, there are 25 additional sources of CO_2 emissions (Figure ES-5).

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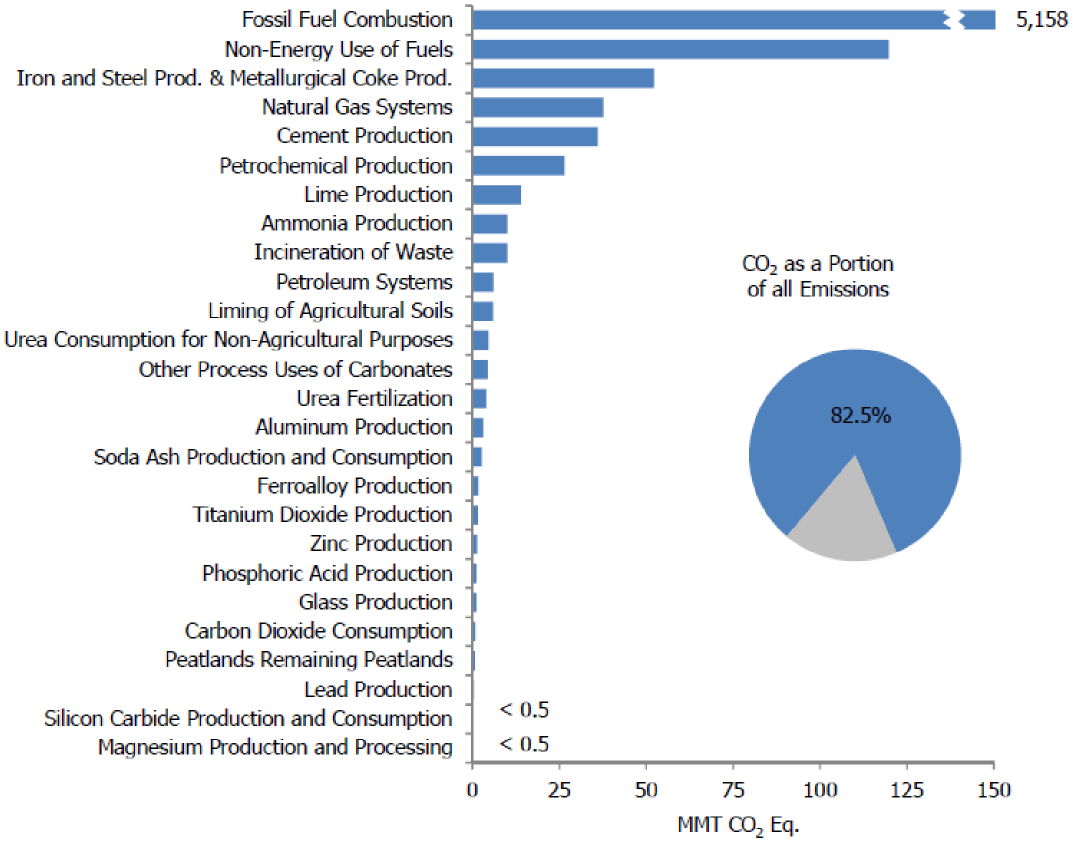
[12] The term "flux" is used to describe the net emissions of greenhouse gases to the atmosphere accounting for both the emissions of CO_2 to and the removals of CO_2 from the atmosphere. Removal of CO_2 from the atmosphere is also referred to as "carbon sequestration."

[13] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Statistics 2013* < http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm> EIA (2013).

Figure ES-5: 2013 Sources of CO_2 Emissions

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Note: Electricity generation also includes emissions of less than 0.05 MMT CO_2 Eq. from geothermal-based generation.

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 77 percent of GWP-weighted emissions since 1990, and is approximately 77 percent of total GWP-weighted emissions in 2013. Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 0.4 percent from 1990 to 2013. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 24 years, (2) an overall growth in emissions from electricity generation and transportation activities, along with (3) a general decline in the carbon intensity of fuels combusted for energy in recent years by most sectors of the economy. Between 1990 and 2013, CO_2 emissions from fossil fuel combustion increased from 4,740.7 MMT CO_2 Eq. to 5,157.7 MMT CO_2 Eq., an 8.8 percent total increase over the twenty-four-year period. From 2012 to 2013, these emissions increased by 131.7 MMT CO_2 Eq. (2.6 percent).

Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, energy fuel choices, and seasonal temperatures. In the short term, the overall consumption of fossil fuels in the United States fluctuates primarily 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. In the long term, energy consumption patterns respond to changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and behavioral choices (e.g., walking, bicycling, or telecommuting to work instead of driving).

Figure ES-6: 2013 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

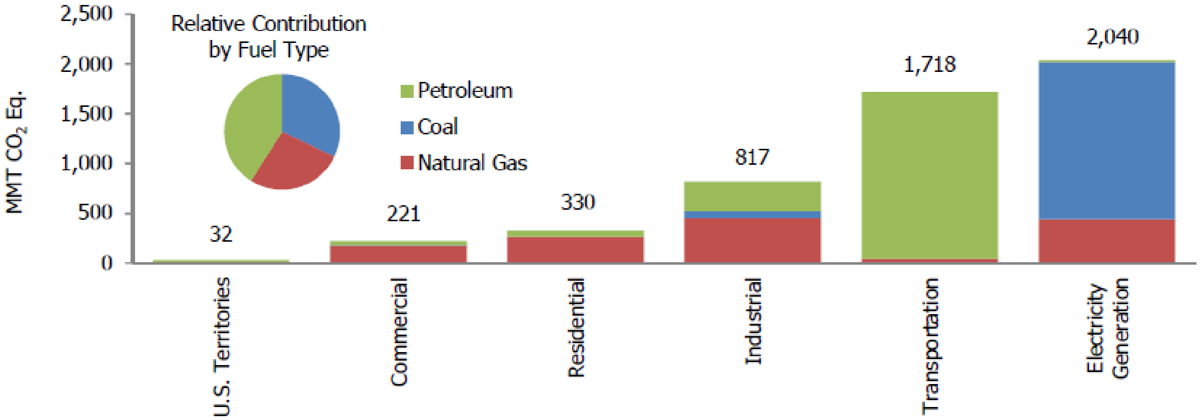
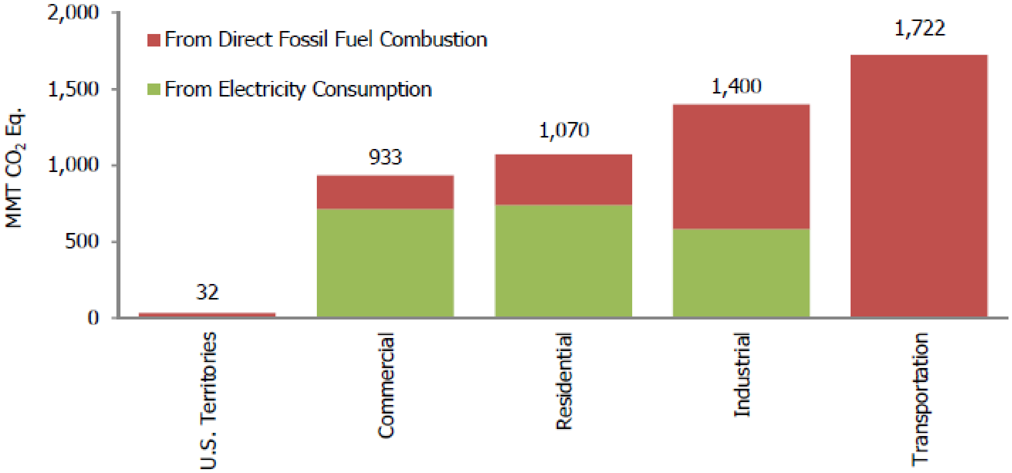


Figure ES-7: 2013 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



The five major fuel consuming sectors contributing to CO_2 emissions from fossil fuel combustion are electricity generation, transportation, industrial, residential, and commercial. CO_2 emissions are produced by the electricity generation sector as they consume fossil fuel to provide electricity to one of the other four sectors, or "end-use" sectors. For the discussion below, electricity generation emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated from the national average mix of fuels according to their carbon intensity. Emissions from electricity generation are also addressed separately after the end-use sectors have been discussed.

Note that emissions from U.S. territories are calculated separately due to a lack of specific consumption data for the individual end-use sectors. Figure ES-6, Figure ES-7, and Table ES-3 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

Table ES-3: CO_2 Emissions from Fossil Fuel Combustion by Fuel Consuming End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Transportation	**1,496.8**	**1,892.5**	**1,724.8**	**1,736.5**	**1,715.8**	**1,704.6**	**1,722.4**
Combustion	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4
Electricity	3.0	4.7	4.5	4.5	4.3	3.9	4.0
Industrial	**1,529.2**	**1,564.4**	**1,329.5**	**1,416.5**	**1,398.8**	**1,377.0**	**1,399.8**
Combustion	842.5	827.8	727.7	775.7	774.1	784.2	817.3
Electricity	686.7	736.6	601.8	640.8	624.7	592.8	582.5
Residential	**931.4**	**1,214.1**	**1,122.6**	**1,174.8**	**1,117.9**	**1,008.4**	**1,070.2**
Combustion	338.3	357.8	336.4	334.7	327.2	283.1	329.6
Electricity	593.0	856.3	786.2	840.1	790.7	725.3	740.6
Commercial	**755.4**	**1,026.7**	**976.7**	**993.2**	**959.1**	**897.4**	**933.3**
Combustion	217.4	223.5	223.5	220.2	221.0	197.1	220.7
Electricity	538.0	803.3	753.2	773.0	738.0	700.3	712.6
U.S. Territories[a]	**27.9**	**49.9**	**43.5**	**46.2**	**39.8**	**38.6**	**32.0**
Total	**4,740.7**	**5,747.7**	**5,197.1**	**5,367.1**	**5,231.3**	**5,026.0**	**5,157.7**
Electricity Generation	**1,820.8**	**2,400.9**	**2,145.7**	**2,258.4**	**2,157.7**	**2,022.2**	**2,039.8**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

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

[a] 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.

Transportation End-Use Sector. When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 33.4 percent of U.S. CO_2 emissions from fossil fuel combustion in 2013. The largest sources of transportation CO_2 emissions in 2013 were passenger cars (42.7 percent), freight trucks (22.8 percent), light duty trucks, which include sport utility vehicles, pickup trucks, and minivans (17.0 percent), commercial aircraft (6.6 percent), pipelines (2.8 percent), rail (2.6 percent), and ships and boats (2.3 percent). Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

In terms of the overall trend, from 1990 to 2013, total transportation CO_2 emissions rose by 15 percent 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 2013). The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 35 percent from 1990 to 2013, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. 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 diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder.

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is consumed by industry, accounted for 27 percent of CO_2 from fossil fuel combustion in 2013. Approximately 58 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from consuming electricity for motors, electric furnaces, ovens, lighting, and other applications. In contrast to the other end-use sectors, emissions from industry have steadily declined 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.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2013. Both sectors relied heavily on electricity for meeting energy demands, with 69 and 76 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Emissions from the residential and commercial end-use sectors have increased by 15 percent and 24 percent since 1990, respectively, due to increasing electricity consumption for lighting, heating, air conditioning, and operating appliances.

Electricity Generation. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators consumed 34 percent of total U.S. energy uses from fossil fuels and emitted 40 percent of the CO_2 from fossil fuel combustion in 2013. The type of fuel combusted by electricity generators has a significant effect on their emissions. For example, some electricity is generated through non-fossil fuel options such as nuclear, hydroelectric, or geothermal energy. Including all electricity generation modes, generators relied on coal for approximately 39 percent of their total energy requirements in 2013.[14] In addition, the coal used by electricity generators accounted for 93 percent of all coal consumed for energy in the United States in 2013.[15] Recently a decrease in the carbon intensity of fuels consumed to generate electricity has occurred due to a decrease in coal consumption, and increased natural gas consumption and other generation sources. Including all electricity generation modes, electricity generators used natural gas for approximately 27 percent of their total energy requirements in 2013.[16]. Across the time series, changes in electricity demand and the carbon intensity of fuels used for electricity generation have a significant impact on CO_2 emissions.

Other significant CO_2 trends included the following:

- CO_2 emissions from non-energy use of fossil fuels have increased by 2.2 MMT CO_2 Eq. (1.9 percent) from 1990 through 2013. Emissions from non-energy uses of fossil fuels were 119.8 MMT CO_2 Eq. in 2013, which constituted 2.2 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- CO_2 emissions from cement production increased every year from 1991 through 2006 (with the exception of a slight decrease in 1997), but decreased in the following years until 2009. Emissions from cement production were at their lowest levels in 2009 (2009 emissions are approximately 29 percent lower than 2008 emissions and 12 percent lower than 1990). Since 2010, emissions have increased slightly. In 2013, emissions from cement production increased by 3.1 percent from the 2012 levels.
- CO_2 sequestration from Land Use, Land-Use Change, and Forestry increased by 105.9 MMT CO_2 Eq. (13.6 percent) from 1990 through 2013. This increase was primarily due to an increase in the rate of net carbon accumulation in forest carbon stocks, particularly in aboveground and belowground tree biomass, and harvested wood pools. Annual carbon accumulation in landfilled yard trimmings and food scraps slowed over this period, while the rate of carbon accumulation in urban trees increased.

Box ES- 2: Use of Ambient Measurements Systems for Validation of Emission Inventories

In following the UNFCCC requirement under Article 4.1 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.[17] Several recent studies have measured emissions at the national or regional level (e.g., Petron 2012, Miller et al. 2013) with results that differ from EPA's estimate of emissions. A recent study (Brandt et al. 2014) reviewed technical literature on methane emissions and estimated methane emissions from all anthropogenic sources (e.g., livestock, oil and gas, waste emissions) to be greater than EPA's estimate. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for greenhouse gas emissions could assist in improving the understanding of inventory estimates. An area of particular interest in EPA's outreach efforts is how these data can be used in a manner consistent with this Inventory report's transparency on its calculation methodologies, and the ability of these techniques to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the

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[14] See < http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states >.

[15] See Table 6.2 Coal Consumption by Sector of EIA 2015a.

[16] See < http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states >.

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

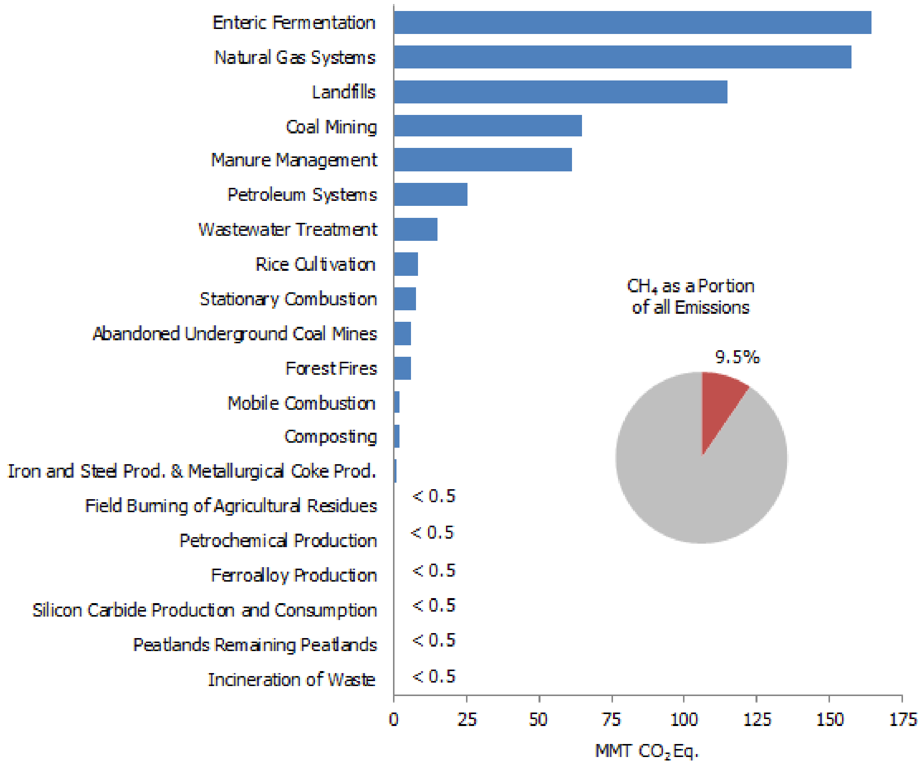
IPCC for this report, versus natural sources and sinks. In working with the research community on ambient measurement and remote sensing techniques to improve national greenhouse gas inventories, EPA relies upon guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[18]

Methane Emissions

Methane (CH_4) is 25 times as effective as CO_2 at trapping heat in the atmosphere (IPCC 2007). Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 152 percent (IPCC 2007 and NOAA/ESRL 2015). Anthropogenic sources of CH_4 include natural gas and petroleum systems, agricultural activities, landfills, coal mining, wastewater treatment, stationary and mobile combustion, and certain industrial processes (see Figure ES-8).

Figure ES-8: 2013 Sources of CH_4 Emissions

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Some significant trends in U.S. emissions of CH_4 include the following:

- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2013, enteric fermentation CH_4 emissions were 164.5 MMT CO_2 Eq. (25.9 percent of total CH_4 emissions), which represents an increase of 0.4 MMT CO_2 Eq. (0.2 percent) since 1990. This increase in emissions from 1990 to 2013 in enteric generally follows the increasing trends in cattle populations. From 1990 to 1995 emissions increased and then decreased from 1996 to 2001, mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions generally increased from 2005 to 2007, though with a slight decrease in 2004, as both dairy and beef populations underwent increases and

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[18] See < http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1003_Uncertainty%20meeting_report.pdf >.

the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again from 2008 to 2013 as beef cattle populations again decreased.

- Natural gas systems were the second largest anthropogenic source category of CH_4 emissions in the United States in 2013 with 157.4 MMT CO_2 Eq. of CH_4 emitted into the atmosphere. Those emissions have decreased by 21.8 MMT CO_2 Eq. (12.2 percent) since 1990. The decrease in CH_4 emissions is largely due to the decrease in emissions from production and distribution. The decrease in production emissions is due to increased use of plunger lifts for liquids unloading, from regulatory reductions such as reductions from hydraulically fractured gas well completions and workovers resulting from the 2012 New Source Performance Standards (NSPS) for oil and gas, and from a variety of voluntary reduction activities. The decrease in distribution emissions is due to a decrease in unprotected steel and cast iron pipelines and their replacement with plastic pipelines. Emissions from field production account for 30 percent of CH_4 emissions and 42 percent of non-combustion CO_2 emissions from natural gas systems in 2013. CH_4 emissions from field production decreased by 21 percent from 1990 to 2013; however, the trend was not stable over the time series – emissions from production generally increased through 2006 due primarily to increases in emissions from pneumatic controllers and hydraulically fractured gas well completions and workovers, and then declined from 2007 to 2013. Reasons for the 2007 to 2013 trend include an increase in plunger lift use for liquids unloading, increased voluntary reductions over that time period (including those associated with pneumatic controllers), and increased reduced emissions completions (RECs) use for well completions and workovers with hydraulic fracturing.

- Landfills are the third largest anthropogenic source of CH_4 emissions in the United States (114.6 MMT CO_2 Eq.), accounting for 18.0 percent of total CH_4 emissions in 2013. From 1990 to 2013, CH_4 emissions from landfills decreased by 71.6 MMT CO_2 Eq. (38.4 percent), with small increases occurring in some interim years. This downward trend in overall emissions can be attributed to a 21 percent reduction in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series (EPA 2010) and an increase in the amount of landfill gas collected and combusted (i.e., used for energy or flared),[19] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.

- Methane emissions from manure management increased by 65.2 percent since 1990, from 37.2 MMT CO_2 Eq. in 1990 to 61.4 MMT CO_2 Eq. in 2013. The majority of this increase was from swine and dairy cow manure, since the general trend in manure management is one of increasing use of liquid systems, which tends to produce greater CH_4 emissions. The increase in liquid systems is the combined result of a shift to larger facilities, and to facilities in the West and Southwest, all of which tend to use liquid systems. Also, new regulations limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site.

Nitrous Oxide Emissions

N_2O is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy-related, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is approximately 300 times more powerful than CO_2 at trapping heat in the atmosphere (IPCC 2007). Since 1750, the global atmospheric concentration of N_2O has risen by approximately 20 percent (IPCC 2007 and NOAA/ESRL 2015). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, stationary fuel combustion, fuel combustion in motor vehicles, manure management and nitric acid production (see Figure ES-9).

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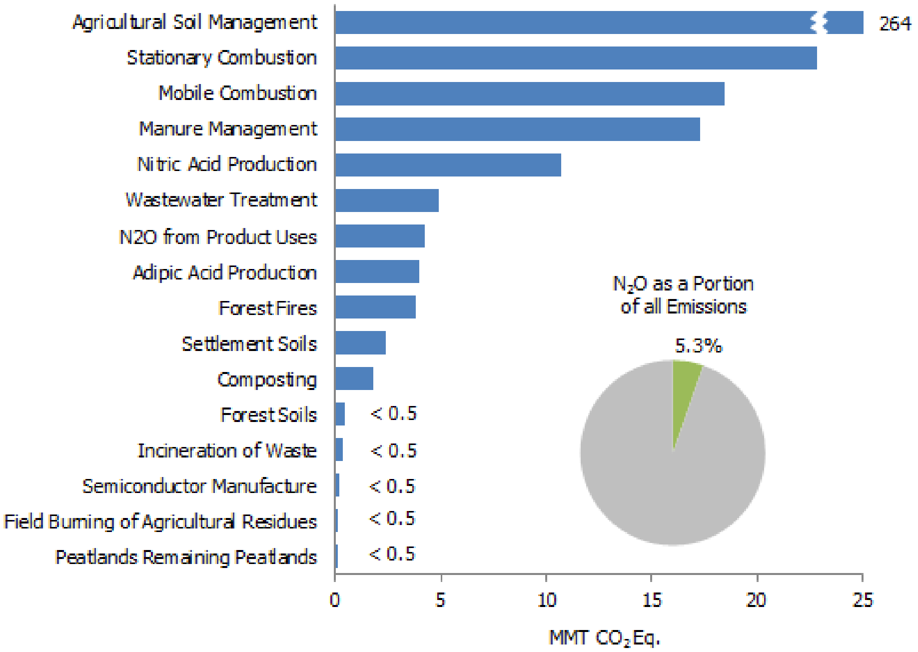
[19] Carbon dioxide emissions from landfills are not included specifically in summing waste sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

Figure ES-9: 2013 Sources of N_2O Emissions

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Some significant trends in U.S. emissions of N_2O include the following:

- Agricultural soils accounted for approximately 74.2 percent of N_2O emissions and 4.0 percent of total emissions in the United States in 2013. Estimated emissions from this source in 2013 were 263.7 MMT CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2013, although overall emissions were 17.7 percent higher in 2013 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.

- N_2O emissions from stationary combustion increased 11.0 MMT CO_2 Eq. (91.9 percent) from 1990 through 2013. N_2O emissions from this source increased primarily as a result of an increase in the number of coal fluidized bed boilers in the electric power sector.

- In 2013, total N_2O emissions from manure management were estimated to be 17.3 MMT CO_2 Eq.; emissions were 13.8 MMT CO_2 Eq. in 1990. These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 25.4 percent increase from 1990 to 2013 and a 0.1 percent decrease from 2012 through 2013. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted.

- N_2O emissions from adipic acid production were 4.0 MMT CO_2 Eq. in 2013, and have decreased significantly since 1990 due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. Emissions from adipic acid production have decreased by 73.8 percent since 1990 and by 76.4 percent since a peak in 1995.

HFC, PFC, SF_6, and NF_3 Emissions

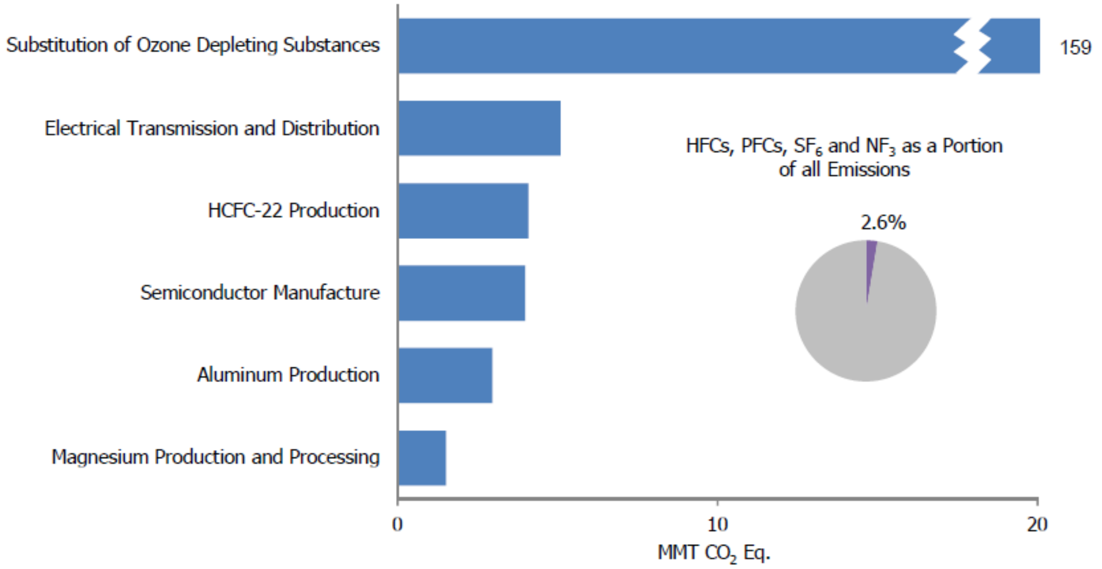
HFCs and PFCs are families of synthetic chemicals that are used as alternatives to Ozone Depleting Substances, which are being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. HFCs and PFCs do not deplete the stratospheric ozone layer, and are therefore acceptable alternatives under the Montreal Protocol.

These compounds, however, along with SF_6 and NF_3, are potent greenhouse gases. In addition to having high global warming potentials, SF_6 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 2013).

Other emissive sources of these gases include HCFC-22 production, electrical transmission and distribution systems, semiconductor manufacturing, aluminum production, and magnesium production and processing (see Figure ES-10).

Figure ES-10: 2013 Sources of HFCs, PFCs, SF_6, and NF_3 Emissions

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Some significant trends in U.S. HFC, PFC, SF_6, and NF_3 emissions include the following:

- Emissions resulting from the substitution of ozone depleting substances (ODS) (e.g., CFCs) have been consistently increasing, from small amounts in 1990 to 158.6 MMT CO_2 Eq. in 2013. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*.
- GWP-weighted PFC, HFC, SF_6, and NF_3 emissions from semiconductor manufacture have increased by 12 percent from 1990 to 2013, due to industrial growth and the adoption of emissions reduction technologies. Within that time span, emissions peaked in 1999, the initial year of the EPA's PFC Reduction / Climate Partnership for the Semiconductor Industry, but have since declined to 4.0 MMT CO_2 Eq. in 2013 (a 56 percent decrease relative to 1999).
- SF_6 emissions from electric power transmission and distribution systems decreased by 79.9 percent (20.3 MMT CO_2 Eq.) from 1990 to 2013. There are two potential causes for 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.
- PFC emissions from aluminum production decreased by 86.2 percent (18.5 MMT CO_2 Eq.) from 1990 to 2013. 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.

ES.3. Overview of Sector Emissions and Trends

In accordance with the UNFCCC decision to set the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) as the standard for Annex I countries at the Nineteenth Conference of the Parties (UNFCCC 2014), Figure ES-11 and Table ES-4 aggregate emissions and sinks by these chapters. Emissions of all gases can be summed from each source category from IPCC guidance. Over the twenty-four-year period of 1990 to 2013, total emissions in the Energy, Industrial Processes and Product Use, and Agriculture sectors grew by 346.2 MMT CO_2 Eq. (6.5 percent), 17.0 MMT CO_2 Eq. (5.0 percent), and 67.0 MMT CO_2 Eq. (14.9 percent), respectively. Emissions from the Waste sector decreased by 67.7 MMT CO_2 Eq. (32.9 percent). Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (magnitude of emissions plus CO_2 removals from all LULUCF source categories) increased by 96.4 MMT CO_2 Eq. (12.7 percent).

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

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

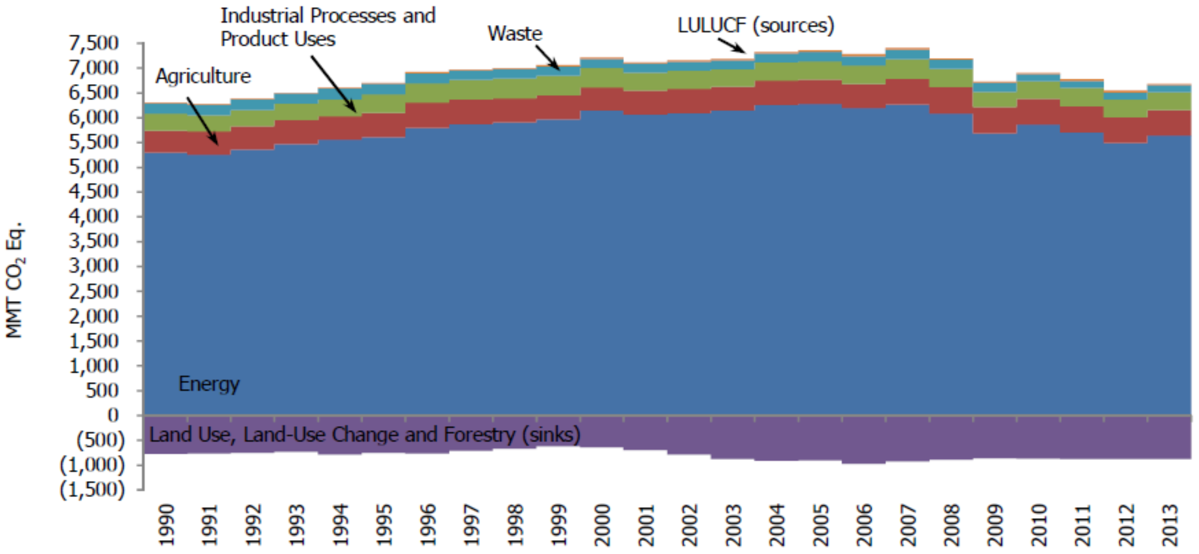


Table ES-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO_2 Eq.)

Chapter/IPCC Sector	1990	2005	2009	2010	2011	2012	2013
Energy	**5,290.5**	**6,273.6**	**5,682.1**	**5,854.6**	**5,702.6**	**5,482.2**	**5,636.6**
Fossil Fuel Combustion	4,740.7	5,747.7	5,197.1	5,367.1	5,231.3	5,026.0	5,157.7
Natural Gas Systems	216.8	206.3	200.2	191.9	194.8	189.2	195.2
Non-Energy Use of Fuels	117.7	138.9	106.0	114.6	108.4	104.9	119.8
Coal Mining	96.5	64.1	79.9	82.3	71.2	66.5	64.6
Petroleum Systems	36.0	28.4	26.2	25.5	26.4	28.3	31.2
Stationary Combustion	20.4	27.6	27.8	29.3	28.4	28.0	30.8
Mobile Combustion	46.9	41.1	26.9	26.0	24.8	22.4	20.6
Incineration of Waste	8.4	12.8	11.6	11.4	10.9	10.7	10.4
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.6	6.4	6.2	6.2
Industrial Processes and Product Use	**342.1**	**367.4**	**314.9**	**353.6**	**371.0**	**361.2**	**359.1**
Substitution of Ozone Depleting Substances	0.3	111.1	136.0	144.4	148.4	153.5	158.6
Iron and Steel Production & Metallurgical Coke Production	100.9	67.5	43.5	56.4	60.7	55.1	53.0
Cement Production	33.3	45.9	29.4	31.3	32.0	35.1	36.1
Petrochemical Production	21.9	28.3	23.8	27.4	26.4	26.5	26.6
Lime Production	11.7	14.6	11.4	13.4	14.0	13.7	14.1

Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2
Aluminum Production	28.3	7.6	4.9	4.6	6.8	6.4	6.2
Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.4	4.7	4.0	4.4	4.7
Other Process Uses of Carbonates	4.9	6.3	7.6	9.6	9.3	8.0	4.4
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Semiconductor Manufacture	3.6	4.7	3.1	3.8	4.9	4.5	4.2
HCFC-22 Production	46.1	20.0	6.8	8.0	8.8	5.5	4.1
Adipic Acid Production	15.2	7.1	2.7	4.2	10.2	5.5	4.0
Soda Ash Production and Consumption	2.7	2.9	2.5	2.6	2.6	2.7	2.7
Ferroalloy Production	2.2	1.4	1.5	1.7	1.7	1.9	1.8
Titanium Dioxide Production	1.2	1.8	1.6	1.8	1.7	1.5	1.6
Magnesium Production and Processing	5.2	2.7	1.6	2.1	2.8	1.7	1.5
Zinc Production	0.6	1.0	0.9	1.2	1.3	1.5	1.4
Phosphoric Acid Production	1.6	1.4	1.0	1.1	1.2	1.1	1.2
Glass Production	1.5	1.9	1.0	1.5	1.3	1.2	1.2
Carbon Dioxide Consumption	1.5	1.4	1.8	1.2	0.8	0.8	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**448.7**	**494.5**	**523.3**	**524.8**	**522.1**	**523.0**	**515.7**
Agricultural Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7
Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5
Manure Management	51.0	72.8	76.7	78.0	78.7	81.0	78.7
Rice Cultivation	9.2	8.9	9.4	11.1	8.5	9.3	8.3
Field Burning of Agricultural Residues	0.4	0.3	0.4	0.4	0.4	0.4	0.4
Land Use, Land-Use Change, and Forestry	**13.8**	**25.5**	**20.6**	**20.3**	**36.1**	**39.8**	**23.3**
Forest Fires	4.2	13.8	9.7	7.9	24.2	26.0	9.7
Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Settlement Soils	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Peatlands Remaining Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8
Forest Soils	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Waste	**206.0**	**189.2**	**181.8**	**145.5**	**144.9**	**138.9**	**138.3**
Landfills	186.2	165.5	158.1	121.8	121.3	115.3	114.6
Wastewater Treatment	19.0	20.2	20.2	20.2	20.1	20.0	20.0
Composting	0.7	3.5	3.6	3.5	3.5	3.7	3.7
Total Emissions	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**
Total Sinks[a]	**(775.8)**	**(911.9)**	**(870.9)**	**(871.6)**	**(881.0)**	**(880.4)**	**(881.7)**
Net Emissions (Sources and Sinks)	**5,525.2**	**6,438.3**	**5,851.9**	**6,027.2**	**5,895.6**	**5,664.7**	**5,791.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Sinks (i.e., CO_2 removals) are only included in Net Emissions total. Refer to Table ES-5 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

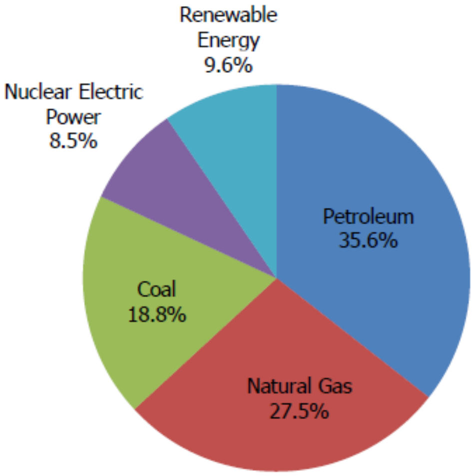
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2013. In 2013, approximately 82 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 18 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-12). Energy-related activities are also responsible for CH_4 and N_2O

emissions (41 percent and 12 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 84.5 percent of total U.S. greenhouse gas emissions in 2013.

Figure ES-12: 2013 U.S. Energy Consumption by Energy Source



Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) section includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. This section includes sources of emissions formerly represented in the "Industrial Processes" and "Solvent and Other Product Use" sectors in prior versions of this report.

Greenhouse gas emissions are produced as the by-products of many non-energy-related industrial activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2, CH_4, and N_2O. These processes include iron and steel production and metallurgical coke production, cement production, ammonia production, urea consumption, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and consumption, titanium dioxide production, phosphoric acid production, ferroalloy production, CO_2 consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, zinc production, and N_2O from product uses. Industrial processes also release HFCs, PFCs, SF_6, and NF_3. In addition to their use as ODS substitutes, HFCs, PFCs, SF_6, NF_3, and other fluorinated compounds are employed and emitted by a number of other industrial sources in the United States. These industries include aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. Overall, emission sources in the Industrial Process and Product Use chapter account for 5.4 percent of U.S. greenhouse gas emissions in 2013.

Agriculture

The Agriculture chapter contains anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and agricultural CO_2 fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry chapter). 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, and field burning of agricultural residues. CH_4 and N_2O were the primary greenhouse gases emitted by agricultural activities. CH_4 emissions from enteric fermentation and manure management represented 25.9 percent and 9.6 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2013. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2013, accounting for 74.2 percent. In 2013, emission sources accounted for in the Agricultural chapters were responsible for 7.7 percent of total U.S. greenhouse gas emissions.

Land Use, Land-Use Change, and Forestry

The Land Use, Land-Use Change, and Forestry chapter contains emissions of CH_4 and N_2O, and emissions and removals of CO_2 from forest management, other land-use activities, and land-use change. Forest management practices, tree planting in urban areas, the management of agricultural soils, and the landfilling of yard trimmings and food scraps resulted in a net removal of CO_2 (sequestration of C) in the United States. Forests (including vegetation, soils, and harvested wood) accounted for 88 percent of total 2013 CO_2 removals, urban trees accounted for 10 percent, mineral and organic soil carbon stock changes accounted for less than 0.5 percent, and landfilled yard trimmings and food scraps accounted for 1.4 percent of the total CO_2 removals in 2013. The net forest sequestration is a result of net forest growth and increasing forest area, as well as a net accumulation of carbon stocks in harvested wood pools. The net sequestration in urban forests is a result of net tree growth in these areas. In agricultural soils, mineral and organic soils sequester approximately 2.4 times as much C as is emitted from these soils through liming and urea fertilization. The mineral soil C sequestration is largely due to the conversion of cropland to permanent pastures and hay production, a reduction in summer fallow areas in semi-arid areas, an increase in the adoption of conservation tillage practices, and an increase in the amounts of organic fertilizers (i.e., manure and sewage sludge) applied to agriculture lands. The landfilled yard trimmings and food scraps net sequestration is due to the long-term accumulation of yard trimming carbon and food scraps in landfills.

Land use, land-use change, and forestry activities in 2013 resulted in a C sequestration (i.e., total sinks) of 881.7 MMT CO_2 Eq. (Table ES-5).[20] This represents an offset of 13.2 percent of total (i.e., gross) greenhouse gas emissions in 2013. Emissions from land use, land-use change and forestry activities in 2013 represent 0.3 percent of total greenhouse gas emissions.[21] Between 1990 and 2013, total land use, land-use change, and forestry C sequestration increased by 13.6 percent, primarily due to an increase in the rate of net C accumulation in forest C stocks, particularly in aboveground and belowground tree biomass, and harvested wood pools. Annual C accumulation in landfilled yard trimmings and food scraps slowed over this period, while the rate of annual C accumulation increased in urban trees.

CO_2 removals are presented in Table ES-5 along with CO_2, CH_4, and N_2O emissions for Land Use, Land-Use Change, and Forestry source categories. Liming of agricultural soils and urea fertilization in 2013 resulted in CO_2 emissions of 9.9 MMT CO_2 Eq. (9,936 kt). Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO_2 emissions of 0.8 MMT CO_2 Eq. (770 kt) and CH_4 and N_2O emissions of less than 0.05 MMT CO_2 Eq. each. The application of synthetic fertilizers to forest soils in 2013 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt). N_2O emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions. Additionally, N_2O emissions from fertilizer application to settlement soils in 2013 accounted for 2.4 MMT CO_2 Eq. (8 kt). This represents an increase of 77 percent since 1990. Forest fires in 2013 resulted in CH_4 emissions of 5.8 MMT CO_2 Eq. (233 kt), and in N_2O emissions of 3.8 MMT CO_2 Eq. (13 kt).

Table ES-5: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2009	2010	2011	2012	2013
CO_2	**(767.7)**	**(903.0)**	**(862.6)**	**(862.0)**	**(872.1)**	**(869.6)**	**(871.0)**
Forest Land Remaining Forest Land: Changes in Forest Carbon Stock[a]	(639.4)	(807.1)	(764.9)	(765.4)	(773.8)	(773.1)	(775.7)

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[20] The total sinks value includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland.*

[21] The emissions value includes the CO_2, CH_4, and N_2O emissions reported for *Forest Fires, Forest Soils, Liming of Agricultural Soils, Urea Fertilization, Settlement Soils,* and *Peatlands Remaining Peatlands*.

Cropland Remaining Cropland: Changes in Agricultural Soil Carbon Stock	(65.2)	(28.0)	(27.5)	(25.9)	(25.8)	(25.0)	(23.4)
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Cropland Remaining Cropland: Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Land Converted to Cropland	24.5	19.8	16.2	16.2	16.2	16.1	16.1
Grassland Remaining Grassland	(1.9)	4.2	11.7	11.7	11.7	11.5	12.1
Land Converted to Grassland	(7.4)	(9.0)	(8.9)	(8.9)	(8.9)	(8.8)	(8.8)
Settlements Remaining Settlements: Changes in Urban Tree Carbon Stock[b]	(60.4)	(80.5)	(85.0)	(86.1)	(87.3)	(88.4)	(89.5)
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8
Other: Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(12.5)	(13.2)	(13.2)	(12.8)	(12.6)
CH_4	**2.5**	**8.3**	**5.8**	**4.8**	**14.6**	**15.7**	**5.8**
Forest Land Remaining Forest Land: Forest Fires	2.5	8.3	5.8	4.7	14.6	15.7	5.8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.1**	**8.3**	**6.5**	**6.0**	**12.6**	**13.3**	**6.7**
Forest Land Remaining Forest Land: Forest Fires	1.7	5.5	3.8	3.1	9.6	10.3	3.8
Forest Land Remaining Forest Land: Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Settlements Remaining Settlements: Settlement Soils[d]	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total Flux[e]	**(762.1)**	**(886.4)**	**(850.2)**	**(851.3)**	**(844.9)**	**(840.6)**	**(858.5)**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Less than 0.05 MMT CO_2 Eq.

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[d] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

[e] "Total Flux" is defined as the sum of positive emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

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

Waste

The Waste chapter contains emissions from waste management activities (except incineration of waste, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic greenhouse gas emissions in the Waste chapter, accounting for 82.9 percent of this chapter's emissions, and 18.0 percent of total U.S. CH_4 emissions.[22] Additionally, wastewater treatment accounts for 14.4 percent of Waste emissions, 2.4 percent of U.S. CH_4 emissions, and 1.4 percent of U.S. N_2O emissions. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.0 MMT CO_2 Eq. and 1.8 MMT CO_2 Eq., respectively. Overall, emission sources accounted for in the Waste chapter generated 2.1 percent of total U.S. greenhouse gas emissions in 2013.

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[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.

ES.4. Other Information

Emissions by Economic Sector

Throughout the Inventory of U.S. Greenhouse Gas Emissions and Sinks report, emission estimates are grouped into five sectors (i.e., chapters) defined by the IPCC: Energy; Industrial Processes and Product Use; Agriculture; Land Use, Land-Use Change, and Forestry; and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines, it is also useful to allocate emissions into more commonly used sectoral categories. This section reports emissions by the following economic sectors: Residential, Commercial, Industry, Transportation, Electricity Generation, Agriculture, and U.S. Territories.

Table ES-6 summarizes emissions from each of these sectors, and Figure ES-13 shows the trend in emissions by sector from 1990 to 2013.

Figure ES-13: Emissions Allocated to Economic Sectors

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

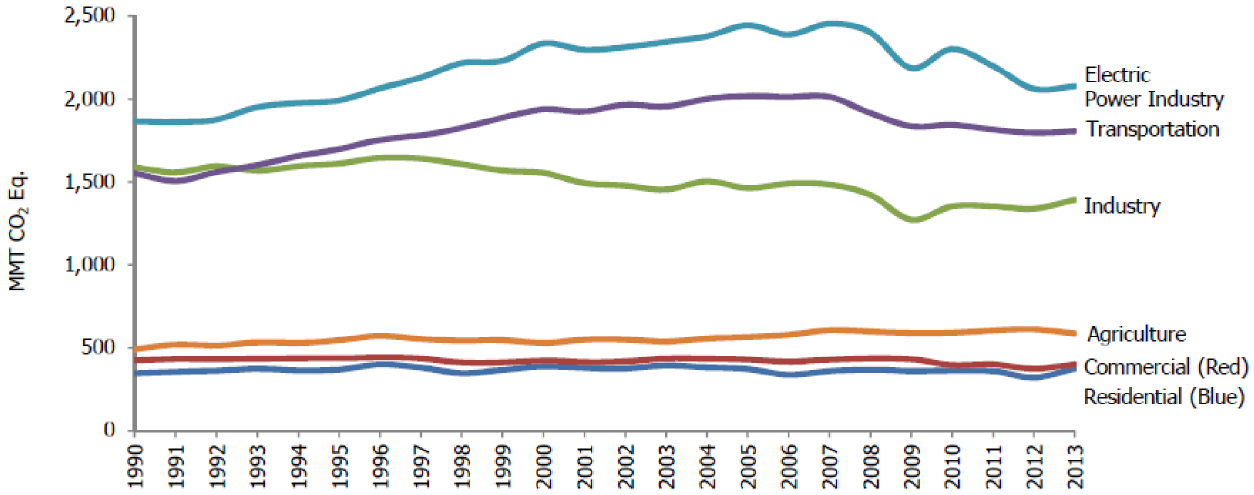

Table ES-6: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

Implied Sectors	1990	2005	2009	2010	2011	2012	2013
Electric Power Industry	1,864.8	2,443.9	2,185.7	2,300.5	2,198.1	2,060.8	2,077.0
Transportation	1,551.3	2,017.7	1,835.3	1,843.5	1,815.4	1,795.9	1,806.2
Industry	1,587.7	1,462.8	1,272.5	1,353.3	1,353.0	1,338.9	1,392.1
Agriculture	492.5	565.0	588.8	590.8	605.5	611.6	586.8
Commercial	424.8	429.8	431.9	396.4	400.7	374.3	401.1
Residential	346.3	372.8	360.9	363.7	360.5	321.5	375.0
U.S. Territories	33.7	58.2	47.6	50.6	43.5	42.1	34.8
Total Emissions	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**
Total Sinks[a]	**(775.8)**	**(911.9)**	**(870.9)**	**(871.6)**	**(881.0)**	**(880.4)**	**(881.7)**
Net Emissions (Sources and Sinks)	**5,525.2**	**6,438.3**	**5,851.9**	**6,027.2**	**5,895.6**	**5,664.7**	**5,791.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Sinks (i.e., CO_2 removals) are only included in the Net Emissions total. Refer to Table ES-5 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

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

Using this categorization, emissions from electricity generation accounted for the largest portion (31 percent) of U.S. greenhouse gas emissions in 2013. Transportation activities, in aggregate, accounted for the second largest portion (27 percent), while emissions from industry accounted for the third largest portion (21 percent) of U.S. greenhouse gas emissions in 2013. In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade. The long-term decline in these emissions has been due to 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 21 percent of U.S. greenhouse gas emissions were contributed by, in order of importance, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 9 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. The commercial and residential sectors each accounted for 6 percent of emissions and U.S. Territories accounted for 1 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. CO_2 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, and landfilling of yard trimmings.

Electricity is ultimately consumed in the economic sectors described above. Table ES-7 presents greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electricity generation were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity.[23] 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 transmission and distribution systems.

When emissions from electricity are distributed among these sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (29 percent and 27 percent, respectively) in 2013. The residential and commercial sectors contributed the next largest shares of total U.S. greenhouse gas emissions in 2013. Emissions from these sectors increase substantially when emissions from electricity are included, due to their relatively large share of electricity consumption (e.g., lighting, appliances, etc.). In all sectors except agriculture, CO_2 accounts for more than 80 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Figure ES-14 shows the trend in these emissions by sector from 1990 to 2013.

Table ES-7: U.S Greenhouse Gas Emissions by Economic Sector with Electricity-Related Emissions Distributed (MMT CO_2 Eq.)

Implied Sectors	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
Industry	2,229.7	2,148.5	1,817.7	1,937.7	1,923.9	1,880.9	1,922.6
Transportation	1,554.4	2,022.5	1,839.9	1,848.1	1,819.7	1,799.8	1,810.3
Residential	953.6	1,244.4	1,161.8	1,219.5	1,166.0	1,060.6	1,129.1
Commercial	975.8	1,247.5	1,199.2	1,183.8	1,152.6	1,088.0	1,126.7
Agriculture	553.9	629.1	656.6	659.2	670.9	673.7	649.4
U.S. Territories	33.7	58.2	47.6	50.6	43.5	42.1	34.8
Total Emissions	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**
Total Sinks[a]	**(775.8)**	**(911.9)**	**(870.9)**	**(871.6)**	**(881.0)**	**(880.4)**	**(881.7)**
Net Emissions (Sources and Sinks)	**5,525.2**	**6,438.3**	**5,851.9**	**6,027.2**	**5,895.6**	**5,664.7**	**5,791.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Emissions from electricity generation are allocated based on aggregate electricity consumption in each end-use sector.

[a] Sinks (i.e., CO_2 removals) are only included in the Net Emissions total. Refer to Table ES-5 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

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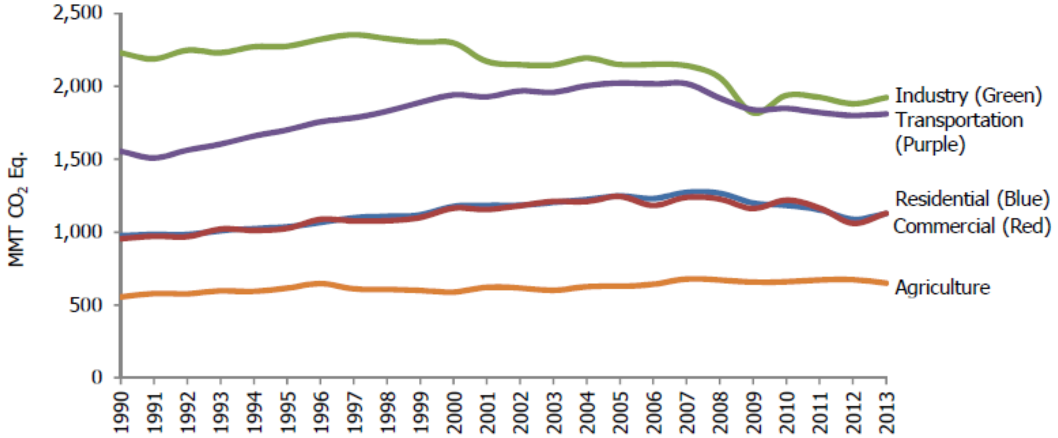
[23] Emissions were not distributed to U.S. territories, since the electricity generation sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration. See Table 2-12 for more detailed data.

Figure ES-14: Emissions with Electricity Distributed to Economic Sectors

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



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

Total emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of electricity consumption, because the electric power industry—utilities and non-utilities combined—was the largest source of U.S. greenhouse gas emissions in 2013; (4) emissions per unit of total gross domestic product as a measure of national economic activity; and (5) emissions per capita.

Table ES-8 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.3 percent since 1990. Since 1990, this rate is slightly slower than that for total energy and for fossil fuel consumption, and much slower than that for electricity consumption, overall gross domestic product and national population (see Figure ES-15).

Table ES-8: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990		2005		2009	2010	2011	2012	2013	Avg. Annual Growth Rate
Greenhouse Gas Emissions[a]	100		117		107	109	108	104	106	0.3%
Energy Consumption[b]	100		118		112	116	115	112	115	0.6%
Fossil Fuel Consumption[b]	100		119		108	112	110	107	110	0.4%
Electricity Consumption[b]	100		134		131	137	137	135	135	1.3%
GDP[c]	100		159		161	165	168	172	175	2.5%
Population[d]	100		118		123	124	125	125	126	1.0%

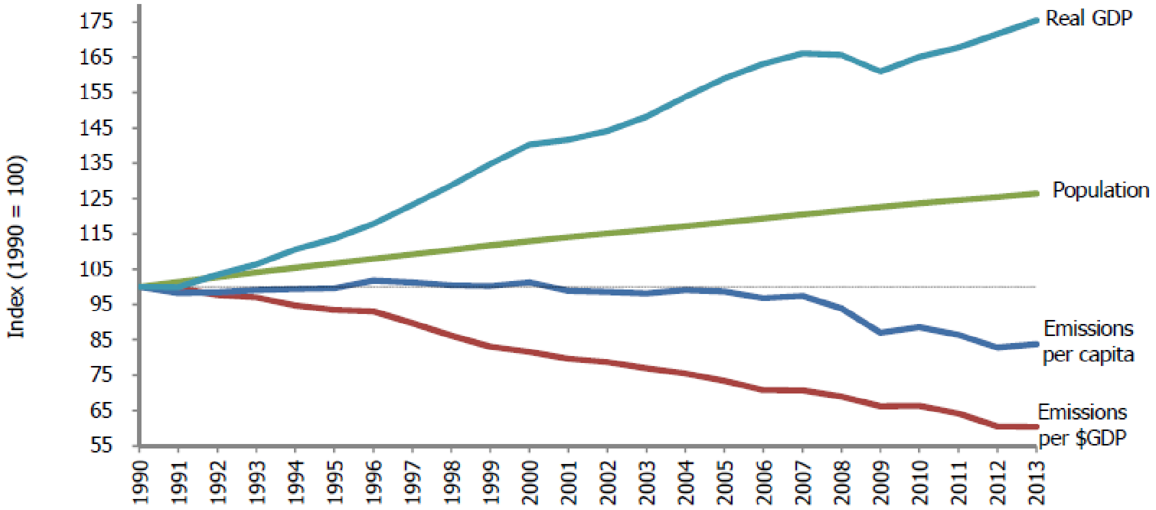
[a] GWP-weighted values

[b] Energy content-weighted values (EIA 2015a)

[c] Gross Domestic Product in chained 2009 dollars (BEA 2014)

[d] U.S. Census Bureau (2014)

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



Source: BEA (2014), U.S. Census Bureau (2014), and emission estimates in this report.

Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals."[24] By definition, key categories are sources or sinks that have the greatest contribution to the absolute overall level of national emissions in any of the years covered by the time series. In addition, when an entire time series of emission estimates is prepared, a thorough investigation of key categories must also account for the influence of trends of individual source and sink categories. Finally, a qualitative evaluation of key categories should be performed, in order to capture any key categories that were not identified in either of the quantitative analyses.

Figure ES-16 presents 2013 emission estimates for the key categories as defined by a level analysis (i.e., the contribution of each source or sink category to the total inventory level). The UNFCCC reporting guidelines request that key category analyses be reported at an appropriate level of disaggregation, which may lead to source and sink category names which differ from those used elsewhere in the Inventory report. For more information regarding key categories, see Section 1.5: Key Categories and Annex 1.

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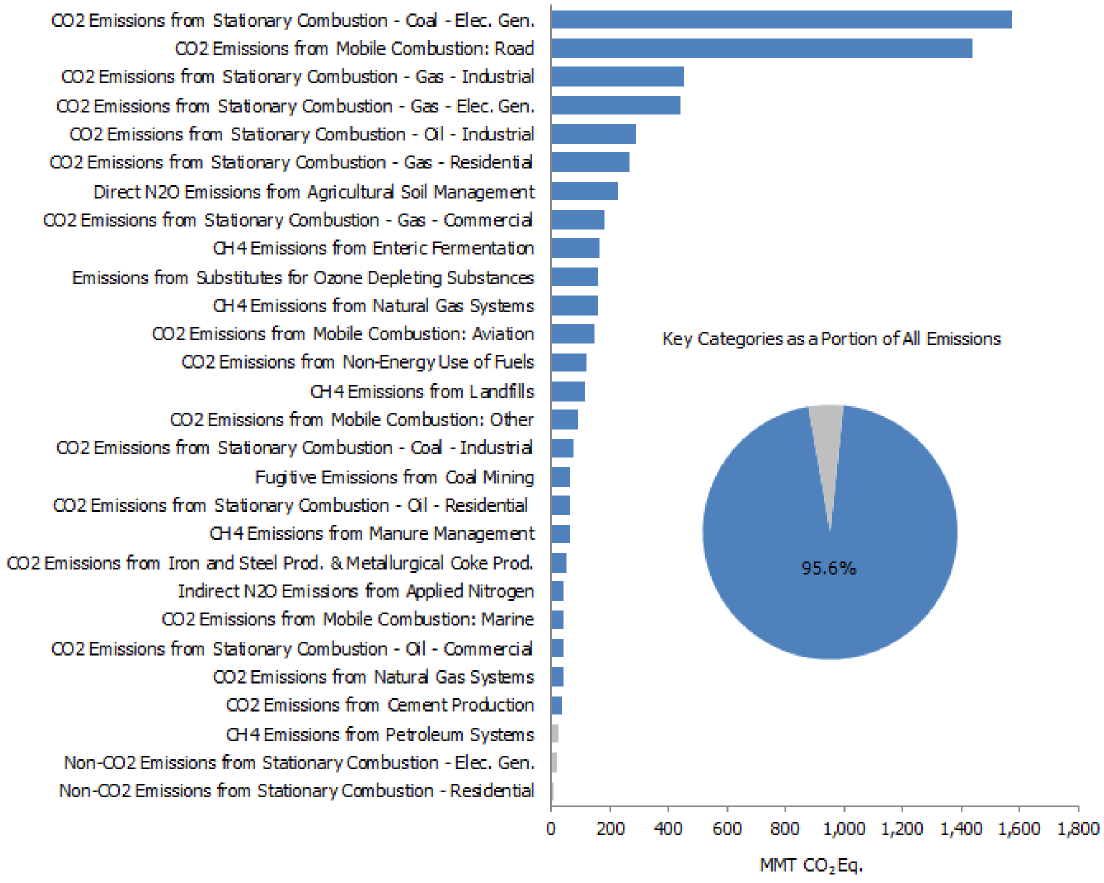
[24] See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006). <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html>

Figure ES-16: 2013 Key Categories



Note: For a complete discussion of the key category analysis, see Annex 1. Blue bars indicate either an Approach 1, or Approach 1 *and* Approach 2 level assessment key category. Gray bars indicate solely an Approach 2 level assessment key category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks to continually improve the quality, transparency, and credibility 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. While QA/QC has always been an integral part of the U.S. national system for inventory development, the procedures followed for the current inventory have been formalized in accordance with the QA/QC plan and the UNFCCC reporting guidelines.

Uncertainty Analysis of Emission Estimates

While the current U.S. emissions inventory provides a solid foundation for the development of a more detailed and comprehensive national inventory, there are uncertainties associated with the emission estimates. Some of the current estimates, such as those for CO_2 emissions from energy-related activities and cement processing, are considered to have low uncertainties. For some other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated increases the uncertainty associated with the estimates presented. Acquiring a better understanding of the uncertainty associated with inventory estimates is an important step in helping to prioritize future work and improve the overall quality of the Inventory. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines* (IPCC 2006) and require that countries provide single estimates of uncertainty for source and sink categories.

Currently, a qualitative discussion of uncertainty is presented for all source and sink categories. Within the discussion of each emission source, specific factors affecting the uncertainty surrounding the estimates are discussed. Most sources also contain a quantitative uncertainty assessment, in accordance with UNFCCC reporting guidelines.

Box ES- 3: Recalculations of Inventory Estimates

Each year, emission and sink estimates are recalculated and revised for all years in the Inventory of U.S. Greenhouse Gas Emissions and Sinks, as attempts are made to improve both the analyses themselves, through the use of better methods or data, and the overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, “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; new inventory methods become available; and for correction of errors.” 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.

In each Inventory report, the results of all methodology changes and historical data updates are presented in the "Recalculations and Improvements" chapter; detailed descriptions of each recalculation are contained within each source's description contained in the report, if applicable. In general, when methodological changes have been implemented, the entire time series (in the case of the most recent Inventory report, 1990 through 2013) has been recalculated to reflect the change, per the *2006 IPCC Guidelines* (IPCC 2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies. References for the data are provided for additional information.

1. Introduction

This report presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 2013. A summary of these estimates is provided in Table 2-1 and Table 2-2 by gas and source category in the Trends in Greenhouse Gas Emissions chapter. The emission estimates in these tables are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis[1] in order to show the relative contribution of each gas to global average radiative forcing. This report also discusses the methods and data used to calculate these emission estimates.

In 1992, the United States signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC). As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2,3]

Parties to the Convention, by ratifying, "shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[4] The United States views this report as an opportunity to fulfill these commitments under the UNFCCC.

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 2003). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries collaborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the UNFCCC are consistent and comparable between nations. The *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* and the *IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry* further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines*. In 2006, the IPCC accepted the *2006 Guidelines for National Greenhouse Gas Inventories* at its Twenty-Fifth Session (Mauritius, April 2006). The *2006 IPCC Guidelines* built

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[1] More information provided in "Global Warming Potentials" section of this chapter on the use of *IPCC Fourth Assessment Report* (AR4) GWP values.

[2] 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).

[3] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://unfccc.int>. (UNEP/WMO 2000)

[4] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12). Subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. See <http://unfccc.int>.

upon the previous bodies of work and include new sources and gases "…as well as updates to the previously published methods whenever scientific and technical knowledge have improved since the previous guidelines were issued. The UNFCCC adopted the *2006 IPCC Guidelines* as the standard methodological approach for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This report presents information in accordance with these guidelines.

Overall, this Inventory of anthropogenic greenhouse gas emissions and sinks provides a common and consistent mechanism through which Parties to the UNFCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change. The Inventory provides a national estimate of sources and sinks for the United States, including all states and U.S. territories.[5] The structure of this report is consistent with the current UNFCCC Guidelines on Annual Inventories (UNFCCC 2014).

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 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.[6] Additionally, the calculated emissions and sinks in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[7] The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. Emissions and sinks provided in this inventory do not preclude alternative examinations, but rather this inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases (GHG) from large GHG emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP). 40 CFR Part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons.[8] Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. The GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective planned improvements sections in this report's chapters, EPA is analyzing the data for use, as applicable, to improve the national estimates presented in this Inventory.

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal and oil, deforestation, land-use changes, and other sources have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our

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[5] U.S. Territories include American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands.

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

[7] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2 >.

[8] See <http://www.epa.gov/climatechange/emissions/ghgrulemaking.html> and <http://ghgdata.epa.gov/ghgp/main.do>.

atmosphere (NOAA 2014). These gases in the atmosphere absorb some of the energy being radiated from the surface of the Earth and then re-radiate this energy with some returning to the Earth's surface, 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, with a portion of these gases occurring naturally from such sources as respiration and volcanic eruptions, without natural concentrations of greenhouse gases the planet's surface would be about 60 ºF cooler than present (EPA 2009). But, as the concentrations of these gases continue to increase in the atmosphere from man-made sources, the Earth's temperature is climbing above past levels. The Earth's averaged land and ocean surface temperature has increased by about 1.2 to 1.9 ºF since 1880. The last three decades have each been the warmest decade successively at the Earth's surface since 1850 (IPCC 2013). Most of the warming in recent decades is very likely the result of human activities. Other aspects of the climate are also changing such as rainfall patterns, snow and ice cover, and sea level.

If greenhouse gases continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase from 0.5 to 8.6 ºF above 1986 through 2005 levels by the end of this century (IPCC 2013). Scientists are certain that human activities are changing the composition of the atmosphere, and that increasing the concentration of greenhouse gases will change the planet's climate. However, they are not sure by how much it will change, at what rate it will change, or what the exact effects will be.[9]

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 2013). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans.[10] A gauge of these changes is called radiative forcing, which is a measure of the influence a perturbation has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system (IPCC 2013). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

> *Human activities are continuing to affect the Earth's energy budget by changing the emissions and resulting atmospheric concentrations of radiatively important gases and aerosols and by changing land surface properties (IPCC 2013).*

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 national greenhouse gas inventories.[11] 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. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and

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[9] For more information see <http://www.epa.gov/climatechange/science>.

[10] For more on the science of climate change, see NRC (2001).

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

tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) 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) and can play a role in affecting cloud formation and lifetime affecting the radiative forcing of clouds and precipitation patterns. Comparatively, however, while the understanding of aerosols has increased in recent years, they still account for the largest contribution to uncertainty estimates in global energy budgets (IPCC 2013).

CO_2, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, 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 (Years) of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.700 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration	399 ppm	1.762-1.893 ppm[a]	0.324-0.326 ppm[a]	7.39-7.79 ppt[a]	79 ppt[f]
Rate of concentration change	1.4 ppm/yr	0.005 ppm/yr[b]	0.26%/yr	Linear[c]	Linear[c]
Atmospheric lifetime (years)	See footnote[d]	12[e]	114[e]	3,200	>50,000

Source: Pre-industrial atmospheric concentrations and rate of concentration changes for all gases are from IPCC (2007). The current atmospheric concentration for CO_2 is from NOAA/ESRL (2015).

[a] The range is the annual arithmetic averages from a mid-latitude Northern-Hemisphere site and a mid-latitude Southern-Hemisphere site for 2012 (CDIAC 2014).

[b] The growth rate for atmospheric CH_4 decreased from over 10 ppb/yr in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 5 ppb/yr.

[c] IPCC (2007) identifies the rate of concentration change for SF_6 and CF_4 as linear.

[d] For a given amount of carbon dioxide 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.

[e] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

[f] The 2011 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2013).

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 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 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, this has been determined to have a negligible effect on climate (IPCC 2013). 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 increase in other greenhouse gases, the total warming is greater than would happen in the absence of water vapor. Aircraft contrails, which consist of water vapor and other substances, are aviation-induced clouds with the same radiative forcing effects as high-altitude cirrus clouds (IPCC 1999).

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. CO_2 concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 398 ppmv in 2013, a 42.4 percent increase (IPCC 2007 and NOAA/ESRL 2015).[12,13] The IPCC definitively states that "the increase of CO_2 … is caused by anthropogenic emissions from the use of fossil fuel as a source of energy and from land use and land use changes, in particular agriculture" (IPCC 2013). 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 Fifth Assessment Report, the IPCC stated "it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together," of which CO_2 is the most important (IPCC 2013).

Methane (CH_4). CH_4 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. CH_4 is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 152 percent since 1750, from a pre-industrial value of about 700 ppb to 1,762 – 1,893 ppb in 2012,[14] although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to about 5 ppb/year. The IPCC has estimated that slightly more than half of the current CH_4 flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use, and waste disposal (IPCC 2007).

CH_4 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, a feedback that increases the atmospheric lifetime of CH_4 (IPCC 2013).

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 20 percent since 1750, from a pre-industrial value of about 270 ppb to 324-326 ppb in 2012,[15] a concentration that has not been exceeded during the last thousand years. N_2O is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2007).

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[12] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2001).

[13] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750-1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2001).

[14] The range is the annual arithmetic averages from a mid-latitude Northern-Hemisphere site and a mid-latitude Southern-Hemisphere site for October 2012 through September 2013 (CDIAC 2014).

[15] The range is the annual arithmetic averages from a mid-latitude Northern-Hemisphere site and a mid-latitude Southern-Hemisphere site for October 2012 through September 2013 (CDIAC 2014).

Ozone (O_3). Ozone is present in both the upper stratosphere,[16] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[17] 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 2013). The depletion of stratospheric ozone and its radiative forcing was expected to reach a maximum in about 2000 before starting to recover.

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 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 2013).

Halocarbons, Perfluorocarbons, Sulfur Hexafluoride, and Nitrogen Triflouride. Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine (CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (halons, methyl bromide, and hydrobromofluorocarbons HFCs) result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is an important greenhouse gas in addition to shielding 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 was placed on the production and importation of HCFCs by non-Article 5[18] countries beginning in 1996, and then followed by 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 of this report for informational purposes.

HFCs, PFCs, SF_6, and NF_3 are not ozone depleting substances, and therefore are not covered under the Montreal Protocol. They are, however, powerful greenhouse gases. HFCs are primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process. Currently, they have a small aggregate radiative forcing impact, but it is anticipated that their contribution to overall radiative forcing will increase (IPCC 2013). PFCs, 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 2013).

Carbon Monoxide. 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.

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[16] 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.

[17] 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.

[18] 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.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect and result from their role in promoting the formation of ozone in the troposphere, are a precursor to nitrate particles (i.e., aerosols) and, to a lesser degree, lower stratosphere, where they have positive radiative forcing effects.[19] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2013). 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.

Nonmethane Volatile Organic Compounds (NMVOCs). Non-CH_4 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.

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 and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous[20] aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning. 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 2013). 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 2013).

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, "despite the large uncertainty ranges on aerosol forcing, there is high confidence that aerosols have offset a substantial portion of GHG forcing" (IPCC 2013).[21] Although because they remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[22] 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 2013). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

Global Warming Potentials

A global warming potential is a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas (see Table 1-2). It is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC 2007). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical

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

[20] Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2013).

[21] The IPCC (2014) defines high confidence as an indication of strong scientific evidence and agreement in this statement.

[22] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer negative forcing effect (i.e., a few years) (IPCC 1996).

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 million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[23] The relationship between kilotons (kt) of a gas and MMT CO_2 Eq. can be expressed as follows:

$$MMT\ CO_2\ Eq. = (kt\ of\ gas) \times (GWP) \times \left(\frac{MMT}{1{,}000\ kt}\right)$$

where,

MMT CO_2 Eq. = Million metric tons of CO_2 equivalent

kt = Kilotons (equivalent to a thousand metric tons)

GWP = Global warming potential

MMT = Million metric tons

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 ±35 percent. Parties to the UNFCCC have also agreed to use GWPs based upon a 100-year time horizon, although other time horizon values are available.

> *…the global warming potential values used by Parties included in Annex I to the Convention (Annex I Parties) to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases shall be those listed in the column entitled "Global warming potential for given time horizon" in table 2.14 of the errata to the contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, based on the effects of greenhouse gases over a 100-year time horizon...*[24]

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[c]
CO_2	[b]	1
CH_4[a]	12	25
N_2O	114	298
HFC-23	270	14,800
HFC-32	4.9	675
HFC-125	29	3,500
HFC-134a	14	1,430
HFC-143a	52	4,470
HFC-152a	1.4	124
HFC-227ea	34.2	3,220
HFC-236fa	240	9,810
HFC-4310mee	15.9	1,640

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

[24] Framework Convention on Climate Change; < http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf >; 31 January 2014; Report of the Conference of the Parties at its nineteenth session; held in Warsaw from 11 to 23 November 2013; Addendum; Part two: Action taken by the Conference of the Parties at its nineteenth session; Decision 24/CP.19; Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention; p. 2. (UNFCCC 2014)

CF_4	50,000	7,390
C_2F_6	10,000	12,200
C_4F_{10}	2,600	8,860
C_6F_{14}	3,200	9,300
SF_6	3,200	22,800
NF_3	740	17,200

Source: (IPCC 2007)

[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 the production of CO_2 is not included.

[b] For a given amount of carbon dioxide 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] 100-year time horizon.

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

In 2013, the IPCC published its *Fifth Assessment Report* (AR5), which provided an updated and more comprehensive scientific assessment of climate change. Within the AR5 report, the GWP values of several gases were revised relative to previous IPCC reports, namely the *IPCC Second Assessment Report* (SAR) (IPCC 1996), the *IPCC Third Assessment Report* (TAR) (IPCC 2001), and the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). Although the AR4 GWP values are used throughout this report, consistent with UNFCCC reporting requirements, it is interesting to review the changes to the GWP values and the impact improved understanding has on the total GWP-weighted emissions of the United States. In the AR5, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function in presenting updated GWP values. Additionally, the atmospheric lifetimes of some gases have been recalculated, and updated background concentrations were used. In addition, the values for radiative forcing and lifetimes have been recalculated for a variety of halocarbons. Table 1-3 presents the new GWP values, relative to those presented in the AR4 and using the 100-year time horizon common to UNFCCC reporting.

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

Gas	SAR	TAR	AR4	AR5[b]	Comparison to AR4		
					SAR	TAR	AR5
CO_2	1	1	1	1	NC	NC	NC
CH_4[a]	21	23	25	28	(4)	(2)	3
N_2O	310	296	298	265	12	(2)	(33)
HFC-23	11,700	12,000	14,800	12,400	(3,100)	(2,800)	(2,400)
HFC-32	650	550	675	677	(25)	(125)	2
HFC-125	2,800	3,400	3,500	3,170	(700)	(100)	(330)
HFC-134a	1,300	1,300	1,430	1,300	(130)	(130)	(130)
HFC-143a	3,800	4,300	4,470	4,800	(670)	(170)	330
HFC-152a	140	120	124	138	16	(4)	14
HFC-227ea	2,900	3,500	3,220	3,350	(320)	280	130
HFC-236fa	6,300	9,400	9,810	8,060	(3,510)	(410)	(1,750)
HFC-4310mee	1,300	1,500	1,640	1,650	(340)	(140)	10
CF_4	6,500	5,700	7,390	6,630	(890)	(1,690)	(760)
C_2F_6	9,200	11,900	12,200	11,100	(3,000)	(300)	(1,100)
C_4F_{10}	7,000	8,600	8,860	9,200	(1,860)	(260)	340
C_6F_{14}	7,400	9,000	9,300	7,910	(1,900)	(300)	(1,390)
SF_6	23,900	22,200	22,800	23,500	1,100	(600)	700
NF_3	NA	10,800	17,200	16,100	NA	(6,400)	700

Source: (IPCC 2013, IPCC 2007, IPCC 2001, IPCC 1996)

NC (No Change)
NA (Not Applicable)
Note: Parentheses indicate negative values.
[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 the production of CO_2 is not included.
[b] The GWPs presented here are the ones most consistent with the methodology used in the AR4 report. The AR5 report has also calculated GWPs (not shown here) where climate-carbon feedbacks have been included for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product.

To comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using AR4 GWP values, as required by the 2013 revision to the UNFCCC reporting guidelines for national inventories.[25] All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use GWPs from other IPCC Assessment Reports are presented in detail in Annex 6.1 of this report. It should be noted that this Inventory represents the first time that the official U.S. greenhouse gas emissions are reported using the AR4 GWP values. The use of IPCC AR4 GWP values for the current Inventory applies across the entire time series of the Inventory (i.e., from 1990 to 2013).[26]

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 U.S. Inventory—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

Within EPA, the Office of Atmospheric Programs (OAP) is the lead office responsible for the emission calculations provided in the Inventory, as well as the completion of the National Inventory Report and the Common Reporting Format tables. EPA's Office of Transportation and Air Quality (OTAQ) is also involved in calculating emissions for the Inventory. While the U.S. Department of State officially submits the annual Inventory to the UNFCCC, EPA's OAP serves as the Inventory focal point for technical questions and comments on the U.S. Inventory. The staff of OAP and OTAQ coordinates the annual methodological choice, activity data collection, and emission calculations at the individual source category level. Within OAP, an inventory coordinator compiles the entire Inventory into the proper reporting format for submission to the UNFCCC, and is responsible for the collection and consistency of cross-cutting issues in the Inventory.

Several other government agencies contribute to the collection and analysis of the underlying activity data used in the Inventory calculations. Formal relationships exist between EPA and other U.S. agencies that 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 military fuel consumption and bunker fuels. Informal relationships also exist with other U.S. agencies to provide activity data for use in EPA's emission calculations. These include: the U.S. Department of Agriculture, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, the National Agricultural Statistics Service, and the Federal Aviation Administration. Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in

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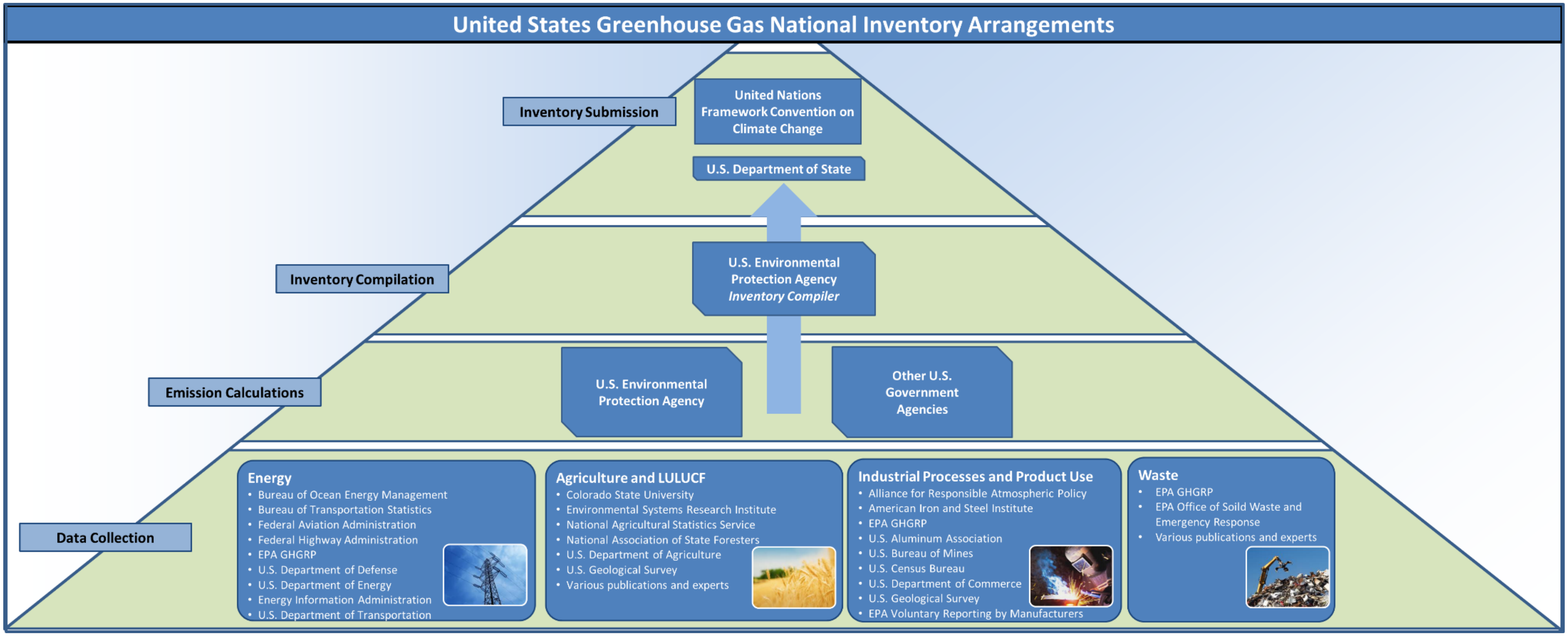
[25] See < http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf >.

[26] ''Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention,'' FCCC/CP/2011/9/Add.2, Decision 6/CP 17, 15 March 2012, available at <http://unfccc.int/resource/docs/2011/cop17/eng/09a02.pdf#page=23>.

voluntary outreach efforts with EPA. Finally, the U.S. Department of State officially submits the Inventory to the UNFCCC each April. Figure 1-1 diagrams the National Inventory Arrangements.

Figure 1-1: National Inventory Arrangements Diagram



1.3 Inventory Process

EPA has a decentralized approach to preparing the annual U.S. Inventory, which consists of a National Inventory Report (NIR) and Common Reporting Format (CRF) tables. The inventory coordinator at EPA is responsible for compiling all emission estimates and ensuring consistency and quality throughout the NIR and CRF tables. Emission calculations for individual sources are the responsibility of individual source leads, who are most familiar with each source category and the unique characteristics of its emissions profile. The individual source leads determine the most appropriate methodology and collect the best activity data to use in the emission calculations, based upon their expertise in the source category, as well as coordinating with researchers and contractors familiar with the sources. A multi-stage process for collecting information from the individual source leads and producing the Inventory is undertaken annually to compile all information and data.

Methodology Development, Data Collection, and Emissions and Sink Estimation

Source leads at EPA collect input data and, as necessary, evaluate or develop the estimation methodology for the individual source categories. For most source 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 category are being developed for the first time, or if the methodology is changing for an existing source category (e.g., the United States is implementing a higher Tiered approach for that source category), then the source category lead will develop a new methodology, gather the most appropriate activity data and emission factors (or in some cases direct emission measurements) for the entire time series, and conduct a special source-specific peer review process involving relevant experts from industry, government, and universities.

Once the methodology is in place and the data are collected, the individual source leads calculate emissions and sink estimates. The source leads then update or create the relevant text and accompanying annexes for the Inventory. Source leads are also responsible for completing the relevant sectoral background tables of the Common Reporting Format, conducting quality assurance and quality control (QA/QC) checks, and uncertainty analyses.

Summary Spreadsheet Compilation and Data Storage

The inventory coordinator at EPA collects the source categories' descriptive text and Annexes, and also aggregates the emission estimates into a summary spreadsheet that links the individual source category spreadsheets together. This summary sheet 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 category, national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Recent Trends sections of the Inventory report. Electronic copies of each year's summary spreadsheet, which contains all the emission and sink estimates for the United States, are kept on a central server at EPA under the jurisdiction of the inventory coordinator.

National Inventory Report Preparation

The NIR is compiled from the sections developed by each individual source lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions from all sources discussed in the chapters. The inventory coordinator then carries out a key category analysis for the Inventory, consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, and in accordance with the reporting requirements of the UNFCCC. Also at this time, the Introduction, Executive Summary, and Recent Trends sections are drafted, to reflect the trends for the most recent year of the current Inventory. The analysis of trends necessitates gathering supplemental data, including weather and temperature conditions, economic activity and gross domestic product, population, atmospheric conditions, and the annual consumption of electricity, energy, and 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. Text boxes are also created to 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 match the specification of the UNFCCC reporting guidelines for National Inventory Reports.

Common Reporting Format Table Compilation

The CRF tables are compiled from individual tables completed by each individual source lead, which contain source emissions and activity data. The inventory coordinator integrates the source data into the UNFCCC's "CRF Reporter" for the United States, assuring consistency across all sectoral tables. The summary reports for emissions, methods, and emission factors used, the overview tables for completeness and quality of estimates, the recalculation tables, the notation key completion tables, and the emission trends tables are then completed by the inventory coordinator. Internal automated quality checks on the CRF Reporter, as well as reviews by the source leads, are completed for the entire time series of CRF tables before submission.

QA/QC and Uncertainty

QA/QC and uncertainty analyses are supervised by the QA/QC and Uncertainty coordinators, who have general oversight over the implementation of the QA/QC plan and the overall uncertainty analysis for the Inventory (see sections on QA/QC and Uncertainty, below). These coordinators work closely with the source leads to ensure that a consistent QA/QC plan and uncertainty analysis is implemented across all inventory sources. The inventory QA/QC plan, detailed in a following section, is consistent with the quality assurance procedures outlined by EPA and IPCC.

Expert and Public Review Periods

During the Expert Review period, a first draft of the document is sent to a select list of technical experts outside of EPA. The purpose of the Expert Review is to encourage feedback on the methodological and data sources used in the current Inventory, especially for sources which have experienced any changes since the previous Inventory.

Once comments are received and addressed, a second draft of the document is released for public review by publishing a notice in the U.S. Federal Register and posting the document on the EPA Web site. The Public Review period allows for a 30 day comment period and is open to the entire U.S. public.

Final Submittal to UNFCCC and Document Printing

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final National Inventory Report and the accompanying Common Reporting Format Reporter database. The U.S. Department of State sends the official submission of the U.S. Inventory to the UNFCCC. The document is then formatted and posted online, available for the public.[1]

1.4 Methodology and Data Sources

Emissions 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). To the extent possible, the present report relies on published activity and emission factor data. Depending on the emission

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[1] See http://epa.gov/climatechange/ghgemissions/usinventoryreport.html.

source category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, etc. Emission factors are factors that relate quantities of emissions to an activity.

The IPCC methodologies provided in the *2006 IPCC Guidelines* represent baseline methodologies for a variety of source categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses the IPCC methodologies when applicable, and supplements them with other available country-specific methodologies and data where possible. Choices made regarding the methodologies and data sources used are provided in conjunction with the discussion of each source category in the main body of the report. Complete documentation is provided in the annexes on the detailed methodologies and data sources utilized in the calculation of each source category.

Box 1-3: IPCC Reference Approach

The 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. 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.

1.5 Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a “[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country’s total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals.”[2] By definition, key categories include those categories that have the greatest contribution to the absolute level of national emissions. In addition, when an entire time series of emission and removal estimates is prepared, a thorough investigation of key categories must also account for the influence of trends and uncertainties of individual source and sink categories. This analysis culls out source and sink categories that diverge from the overall trend in national emissions. Finally, a qualitative evaluation of key categories is performed to capture any categories that were not identified in any of the quantitative analyses.

Approach 1, as defined in the 2006 *IPCC Guidelines* (IPCC 2006), was implemented to identify the key categories for the United States. This analysis was performed twice; one analysis included sources and sinks from the Land Use, Land-Use Change, and Forestry (LULUCF) sector, the other analysis did not include the LULUCF categories. Following Approach 1, Approach 2, as defined in the *2006 IPCC Guidelines* (IPCC 2006), was then implemented to identify any additional key categories not already identified in Approach 1 assessment. This analysis, which includes each source category’s uncertainty assessments (or proxies) in its calculations, was also performed twice to include or exclude LULUCF categories.

In addition to conducting Approach 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the *2006 IPCC Guidelines* (IPCC 2006), was conducted to capture any key categories that were not identified by either quantitative method. One additional key category, international bunker fuels, was identified using this qualitative assessment. International bunker fuels are fuels consumed for aviation or marine international transport activities, and emissions from these fuels are reported separately from totals in accordance

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[2] See Chapter 4 “Methodological Choice and Identification of Key Categories” in IPCC (2006). See < http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>.

with IPCC guidelines. If these emissions were included in the totals, bunker fuels would qualify as a key category according to Approach 1. The amount of uncertainty associated with estimation of emissions from international bunker fuels also supports the qualification of this source category as key, because it would qualify bunker fuels as a key category according to Approach 2. Table 1-4 presents the key categories for the United States (including and excluding LULUCF categories) using emissions and uncertainty data in this report, and ranked according to their sector and global warming potential-weighted emissions in 2013. The table also indicates the criteria used in identifying these categories (i.e., level, trend, Approach 1, Approach 2, and/or qualitative assessments). Annex 1 of this report provides additional information regarding the key categories in the United States and the methodologies used to identify them.

Table 1-4: Key Categories for the United States (1990-2013)

IPCC Source Categories	Gas	Approach 1				Approach 2				Qual^{a}	2013 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											
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		1,575.0
CO_2 Emissions from Mobile Combustion: Road	CO_2	•	•	•	•	•	•	•	•		1,438.9
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•		•			450.8
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		441.9
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•		•	•	•		•			290.6
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•	•	•	•	•		•			267.1
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•	•	•			178.2
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•	•	•	•		148.7
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•	•	•		•		•			119.8
CO_2 Emissions from Mobile Combustion: Other	CO_2	•	•	•	•						92.0
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•		75.8

CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•		•				62.5
CO_2 Emissions from Mobile Combustion: Marine	CO_2	•	•	•	•						38.9
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•						38.6
CO_2 Emissions from Natural Gas Systems	CO_2	•		•		•		•			37.8
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2			•							26.0
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		22.4
CO_2 Emissions from Petroleum Systems	CO_2						•				6.0
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2		•		•						3.9
CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2						•				2.6
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2						•		•		0.0
CH_4 Emissions from Natural Gas Systems	CH_4	•	•	•	•	•	•	•	•		157.4
Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•		64.6
CH_4 Emissions from Petroleum Systems	CH_4	•	•	•	•	•	•	•	•		25.2
Non-CO_2 Emissions from Stationary Combustion - Residential	CH_4					•		•			5.0
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O		•		•	•	•	•	•		19.1
N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•		•		•		14.5
Non-CO_2 Emissions from Stationary Combustion - Industrial	N_2O						•				2.4
International Bunker Fuels[b]	Several									•	100.7
Industrial Processes and Product Use											
CO_2 Emissions from Iron and Steel Production &	CO_2	•	•	•	•	•	•	•	•		52.3

Metallurgical Coke Production											
CO_2 Emissions from Cement Production	CO_2	•		•							36.1
CO_2 Emissions from Petrochemical Production	CO_2			•							26.5
N_2O Emissions from Adipic Acid Production	N_2O		•		•						4.0
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	•	•	•	•	•	•	•	•		158.6
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP		•		•		•		•		5.1
HFC-23 Emissions from HCFC-22 Production	HiGWP	•	•	•	•		•		•		4.1
PFC Emissions from Aluminum Production	HiGWP		•		•						3.0
Agriculture											
CH_4 Emissions from Enteric Fermentation	CH_4	•	•	•	•	•		•			164.5
CH_4 Emissions from Manure Management	CH_4	•	•	•	•	•	•	•	•		61.4
CH_4 Emissions from Rice Cultivation	CH_4					•					8.3
Direct N_2O Emissions from Agricultural Soil Management	N_2O	•	•	•	•	•	•	•	•		224.7
Indirect N_2O Emissions from Applied Nitrogen	N_2O	•		•		•	•	•	•		39.0
Waste											
CH_4 Emissions from Landfills	CH_4	•	•	•	•	•	•	•	•		114.6
Land Use, Land Use Change, and Forestry											
CO_2 Emissions from Land Converted to Cropland	CO_2				•			•	•		16.1
CO_2 Emissions from Grassland Remaining Grassland	CO_2				•			•	•		12.1
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2				•			•	•		(12.6)
CO_2 Emissions from Cropland Remaining Cropland	CO_2			•	•			•	•		(23.4)
CO_2 Emissions from Urban Trees	CO_2			•	•			•	•		(89.5)
CO_2 Emissions from Changes in Forest Carbon Stocks	CO_2			•	•			•	•		(775.7)
CH_4 Emissions from Forest Fires	CH_4							•	•		5.8
N_2O Emissions from Forest Fires	N_2O								•		3.8

Subtotal Without LULUCF	**6,455.5**
Total Emissions Without LULUCF	**6,649.7**
Percent of Total Without LULUCF	**97%**
Subtotal With LULUCF	**5,625.3**
Total Emissions With LULUCF	**5,791.2**
Percent of Total With LULUCF	**97%**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
[a] Qualitative criteria.
[b] Emissions from this source not included in totals.
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. QA/QC plan, Quality Assurance/Quality Control and Uncertainty Management 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:

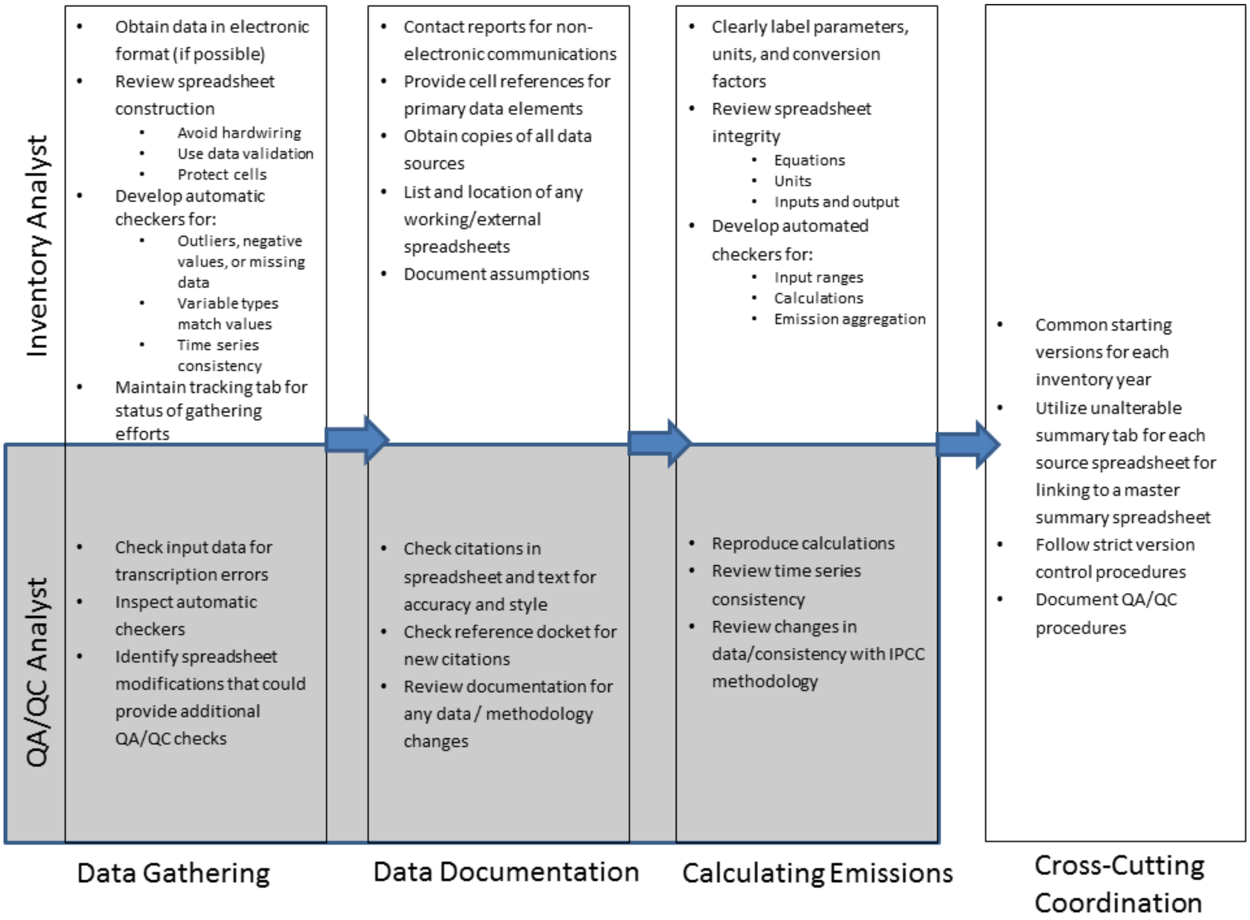
- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures:* application of QA/QC procedures throughout the whole inventory development process from initial data collection, through preparation of the emission estimates, to publication of the Inventory
- *Quality Assurance:* 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)
- *Quality Control*: consideration of secondary data and source-specific checks (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
- *Tier 1 (general) and Tier 2 (source-specific) Checks:* quality controls and checks, as recommended by IPCC Good Practice Guidance
- *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
- *Multi-Year Implementation*: a schedule for coordinating the application of QA/QC procedures across multiple years
- *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.

In addition, based on the national QA/QC plan for the Inventory, source-specific QA/QC plans have been developed for a number of sources. These plans follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific text and spreadsheets of the individual sources. For each greenhouse gas emissions source or sink included in this Inventory, a minimum of a Tier 1 QA/QC analysis has been undertaken. Where QA/QC activities for a particular source go beyond the minimum Tier 1 level, further explanation is provided within the respective source category text.

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 at two stages—an expert review and a public review. While both phases can significantly contribute to inventory quality, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of the inventory data and methods.

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 estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

Figure 1-2: U.S. QA/QC Plan Summary



1.7 Uncertainty Analysis of Emission Estimates

Uncertainty estimates are an essential element of a complete and transparent emissions inventory. Uncertainty information is not intended to dispute the validity of the inventory estimates, but to help prioritize efforts to improve the accuracy of future inventories and guide future decisions on methodological choice. While the U.S. Inventory calculates its emission estimates with the highest possible accuracy, uncertainties are associated to a varying degree with the development of emission estimates for any inventory. Some of the current estimates, such as those for CO_2 emissions from energy-related activities, are considered to have minimal uncertainty associated with them. For some other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated increases the uncertainty surrounding the estimates presented. The UNFCCC reporting guidelines follow the recommendation in the *2006 IPCC Guidelines* (IPCC 2006) and require that countries provide single point estimates for each gas and emission or removal source category. Within the discussion of each emission source, specific factors affecting the uncertainty associated with the estimates are discussed.

Additional research in the following areas could help reduce uncertainty in the U.S. Inventory:

- *Incorporating excluded emission sources*. Quantitative estimates for some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities and industrial processes are not included in the inventory either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex 5 of this report for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report.
- *Improving the accuracy of emission factors*. Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to CH_4 and N_2O emissions from stationary and mobile combustion is highly uncertain.
- *Collecting detailed activity data*. Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of SF_6 from electrical transmission and distribution is limited due to a lack of activity data regarding national SF_6 consumption or average equipment leak rates.

The overall uncertainty estimate for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology. Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions are shown below, in Table 1-5.

The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for individual source categories. Approach 2 uncertainty analysis, employing the Monte Carlo Stochastic Simulation technique, was applied wherever data and resources permitted; further explanation is provided within the respective source category text and in Annex 7. Consistent with the *2006 IPCC Guidelines* (IPCC 2006), over a multi-year timeframe, the United States expects to continue to improve the uncertainty estimates presented in this report.

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

Gas	2013 Emission Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)		Mean[c] (MMT CO_2 Eq.)	Standard Deviation[c]
		Lower Bound[d]	Upper Bound[d]	Lower Bound	Upper Bound		
CO_2	5,505	5,400	5,766	-2%	5%	5,584	95
CH_4[e]	636	573	751	-10%	18%	656	45
N_2O[e]	355	320	445	-10%	25%	376	32
PFC, HFC, SF_6, and NF_3[e]	171	170	190	-1%	11%	180	5
Total	**6,667**	**6,584**	**7,008**	**-1%**	**5%**	**6,795**	**110**

Net Emissions (Sources and Sinks)	**5,785.5**	**5,613**	**6,220**	**-3%**	**8%**	**5,916**	**154**

Notes:

[a] Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed this year. Thus the totals reported in this table exclude approximately 5.7 MMT CO_2 Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory.

[b] 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.

[c] 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.

[d] 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.

[e] 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 2013.

Emissions calculated for the U.S. Inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies, assumptions, and incomplete data. As new information becomes available in the future, the United States will continue to improve and revise its emission estimates. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the emission estimates and for a more detailed discussion of the limitations of the current analysis and plans for improvement. Annex 7 also includes details on the uncertainty analysis performed for selected source categories.

1.8 Completeness

This report, along with its accompanying CRF tables, 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 2013. Although this report is intended to be comprehensive, certain sources have been identified which were excluded from the estimates presented for various reasons. Generally speaking, sources not accounted for in this inventory are excluded due to data limitations or a lack of thorough understanding of the emission process. The United States is continually working to improve upon the understanding of such sources and seeking to find the data required to estimate related emissions. As such improvements are implemented, new emission sources are quantified and included in the Inventory. For a complete list of sources not included, see Annex 5 of this report.

1.9 Organization of Report

In accordance with the revision of the UNFCCC reporting guidelines agreed to at the nineteenth Conference of the Parties (UNFCCC 2014), this Inventory of U.S. Greenhouse Gas Emissions and Sinks is segregated into five sector-specific chapters, listed below in Table 1-6. In addition, chapters on Trends in Greenhouse Gas Emissions and Other information to be considered as part of the U.S. Inventory submission are included.

Table 1-6: IPCC Sector Descriptions

Chapter/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	Anthropogenic 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, CH_4, and N_2O from forest management, other land-use activities, and land-use change.
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/IPCC Sector: Overview of emission trends for each IPCC defined sector

Source category: Description of source pathway and emission trends.

Methodology: Description of analytical methods employed to produce emission estimates and identification of data references, primarily for activity data and emission factors.

Uncertainty and Timeseries Consistency: A discussion and quantification of the uncertainty in emission estimates and a discussion of time-series consistency.

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

Recalculations: 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 source-specific planned improvements, if applicable.

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 1-7.

Table 1-7: 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 and Soil Organic C Stock Changes from Agricultural Soil Management (Cropland and Grassland)
3.13. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands
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. Sulfur Dioxide Emissions
6.4. Complete List of Source Categories
6.5. Constants, Units, and Conversions
6.6. Abbreviations
6.7. Chemical Formulas
ANNEX 7 Uncertainty
7.1. Overview
7.2. Methodology and Results
7.3. Planned Improvements
ANNEX 8 QA/QC Procedures
8.1. Background
8.2. Purpose
8.3. Assessment Factors

2. Trends in Greenhouse Gas Emissions

2.1 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2013, total U.S. greenhouse gas emissions were 6,673.0 MMT or million metric tons CO_2 Eq. Total U.S. emissions have increased by 5.9 percent from 1990 to 2013, and emissions increased from 2012 to 2013 by 2.0 percent (127.9 MMT CO_2 Eq.). The increase from 2012 to 2013 was due to an increase in the carbon intensity of fuels consumed to generate electricity due to an increase in coal consumption, with decreased natural gas consumption. Additionally, cold winter conditions lead to an increase in fuels for the residential and commercial sectors for heating. In 2013 there also was an increase in industrial production across multiple sectors resulting in increases in industrial sector emissions. Lastly, transportation emissions increased as a result of a small increase in vehicle miles traveled (VMT) and fuel use across on-road transportation modes. Since 1990, U.S. emissions have increased at an average annual rate of 0.3 percent. Figure 2-1 through Figure 2-3 illustrate the overall trend in total U.S. emissions by gas, annual changes, and absolute changes since 1990.

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

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

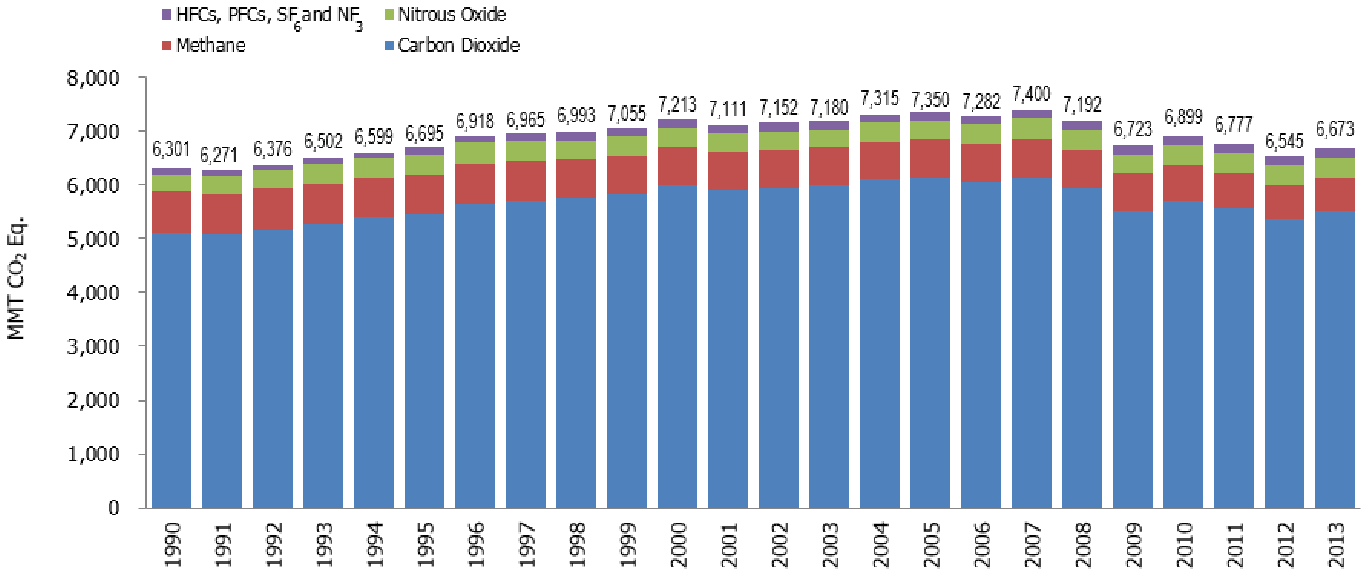


Figure 2-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

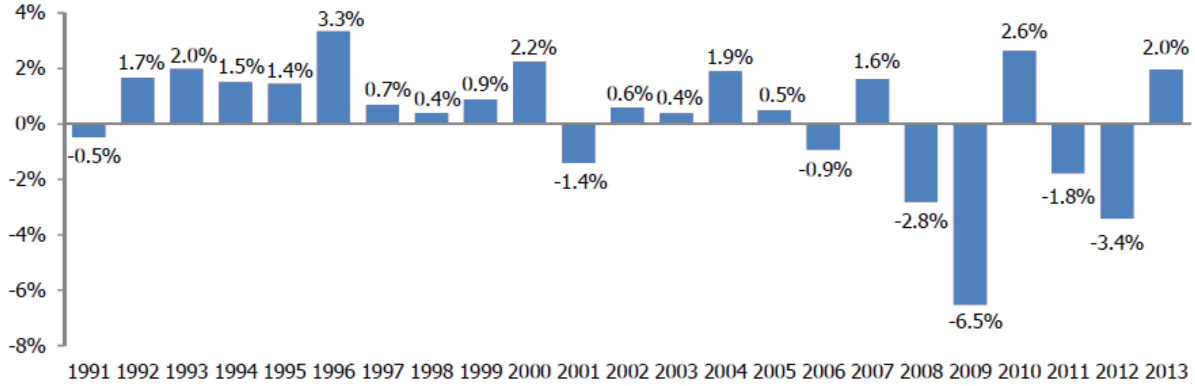
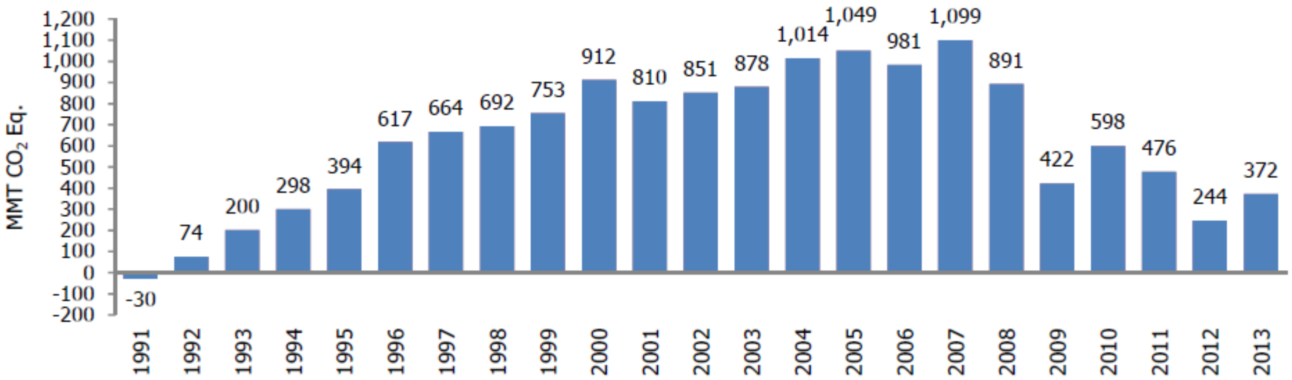


Figure 2-3: Cumulative Change in Annual U.S. Greenhouse Gas Emissions Relative to 1990

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Overall, from 1990 to 2013, total emissions of CO_2 increased by 381.5 MMT CO_2 Eq. (7.4 percent), while total emissions of CH_4 decreased by 109.2 MMT CO_2 Eq. (14.6 percent), and total emissions of N_2O increased 25.3 MMT CO_2 Eq. (7.7 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, SF_6, and NF_3 rose by 74.3 MMT CO_2 Eq. (72.9 percent). 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 GWPs and, in the cases of PFCs SF_6, and NF_3, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by C sequestration in managed forests, trees in urban areas, agricultural soils, and landfilled yard trimmings. These were estimated to offset 13.2 percent of total emissions in 2013.

As the largest contributor to U.S. greenhouse gas emissions, carbon dioxide (CO_2) from fossil fuel combustion has accounted for approximately 77 percent of global warming potential (GWP) weighted emissions for the entire time series since 1990, from 75 percent of total GWP-weighted emissions in 1990 to 77 percent in 2013. Emissions from this source category grew by 8.8 percent (417.0 MMT CO_2 Eq.) from 1990 to 2013 and were responsible for most of the increase in national emissions during this period. From 2012 to 2013, these emissions increased by 2.6 percent (131.7 MMT CO_2 Eq.). Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall consumption of fossil fuels in the United States fluctuates primarily 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 in a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

In the longer-term, energy consumption patterns respond to changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs) and behavioral choices (e.g., walking, bicycling, or telecommuting to work instead of driving).

Energy-related CO_2 emissions also depend on the type of fuel or energy consumed and its carbon (C) intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 emissions because of the lower C content of natural gas.

A brief discussion of the year to year variability in fuel combustion emissions is provided below, beginning with 2009.

From 2009 to 2010, CO_2 emissions from fossil fuel combustion increased by 3.3 percent, which represents one of the largest annual increases in CO_2 emissions from fossil fuel combustion for the twenty four-year period from 1990 to 2013. This increase is primarily due to an increase in economic output from 2009 to 2010, and increased industrial production and manufacturing output (FRB 2014). Carbon dioxide emissions from fossil fuel combustion in the industrial sector increased by 6.6 percent, including increased emissions from the combustion of fuel oil, natural gas and coal. Overall, coal consumption increased by 5.8 percent, the largest annual increase in coal consumption for the twenty four-year period between 1990 and 2013. In 2010, weather conditions remained fairly constant in the winter and were much hotter in the summer compared to 2009, as heating degree days decreased slightly by 0.4 percent and cooling degree days increased by 17.3 percent to their highest levels in the twenty one-year period from 1990 to 2010. As a result of the more energy-intensive summer weather conditions, electricity sales to the residential and commercial end-use sectors in 2010 increased approximately 6.0 percent and 1.8 percent, respectively.

From 2010 to 2011, CO_2 emissions from fossil fuel combustion decreased by 2.5 percent. This decrease is a result of multiple factors including: (1) a decrease in the carbon intensity of fuels consumed to generate electricity due to a decrease in coal consumption, with increased natural gas consumption and a significant increase in hydropower used; (2) a decrease in transportation-related energy consumption due to higher fuel costs, improvements in fuel efficiency, and a reduction in miles traveled; and (3) relatively mild winter conditions resulting in an overall decrease in energy demand in most sectors. Changing fuel prices played a role in the decreasing emissions. A significant increase in the price of motor gasoline in the transportation sector was a major factor leading to a decrease in energy consumption by 1.2 percent. In addition, an increase in the price of coal and a concurrent decrease in natural gas prices led to a 5.7 percent decrease and a 2.5 percent increase in fuel consumption of these fuels by electric generators. This change in fuel prices also reduced the carbon intensity of fuels used to produce electricity in 2011, further contributing to the decrease in fossil fuel combustion emissions.

From 2011 to 2012, CO_2 emissions from fossil fuel combustion decreased by 3.9 percent, with emissions from fossil fuel combustion at their lowest level since 1994. This decrease from 2011 to 2012 is primarily a result of the decrease in the carbon intensity of fuels used to generate electricity due to a slight increase in the price of coal, and a significant decrease in the price of natural gas. The consumption of coal used to generate electricity decreased by 12.3 percent, while consumption of natural gas for electricity generation increased by 20.4 percent. Also, emissions declined in the transportation sector largely due to a small increase in fuel efficiency across different transportation modes and limited new demand for passenger transportation. In 2012, weather conditions remained fairly constant in the summer and were much warmer in the winter compared to 2011, as cooling degree days increased by 1.7 percent while heating degree days decreased 12.6 percent. This decrease in heating degree days resulted in a decreased demand for heating fuel in the residential and commercial sector, which had a decrease in natural gas consumption of 11.7 and 8.0 percent, respectively.

From 2012 to 2013, CO_2 emissions from fossil fuel combustion increased by 2.6 percent, this increase is primarily a result of the increased energy consumption in the residential and commercial sectors, as heating degree days increased 18.5 percent in 2013 as compared to 2012. The cooler weather led to an increase of 16.9 and 12.4 percent direct use of fuels in the residential and commercial sectors, respectively. In addition, there was an increase of 1.2 and 0.9 percent in electricity consumption in the residential and commercial sectors, respectively, due to regions that heat their homes with electricity. The consumption of natural gas used to generate electricity decreased by 10.2 percent due to an increase in the price of natural gas. Electric power plants shifted some consumption from natural gas to coal, and as a result increased coal consumption to generate electricity by 4.2 percent. Lastly, industrial production increased 2.9 percent from 2012 to 2013, resulting in an increase in the in CO_2 emissions from fossil fuel combustion from the industrial sector by 4.2 percent.

Table 2-1 summarizes emissions and sinks from all U.S. anthropogenic sources 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 (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**5,123.7**	**6,134.0**	**5,500.6**	**5,704.5**	**5,568.9**	**5,358.3**	**5,505.2**
Fossil Fuel Combustion	4,740.7	5,747.7	5,197.1	5,367.1	5,231.3	5,026.0	5,157.7
Electricity Generation	1,820.8	2,400.9	2,145.7	2,258.4	2,157.7	2,022.2	2,039.8
Transportation	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4
Industrial	842.5	827.8	727.7	775.7	774.1	784.2	817.3
Residential	338.3	357.8	336.4	334.7	327.2	283.1	329.6
Commercial	217.4	223.5	223.5	220.2	221.0	197.1	220.7
U.S. Territories	27.9	49.9	43.5	46.2	39.8	38.6	32.0
Non-Energy Use of Fuels	117.7	138.9	106.0	114.6	108.4	104.9	119.8
Iron and Steel Production & Metallurgical Coke Production	99.8	66.7	43.0	55.7	60.0	54.3	52.3
Natural Gas Systems	37.6	30.0	32.2	32.3	35.6	34.8	37.8
Cement Production	33.3	45.9	29.4	31.3	32.0	35.1	36.1
Petrochemical Production	21.6	28.1	23.7	27.4	26.4	26.5	26.5
Lime Production	11.7	14.6	11.4	13.4	14.0	13.7	14.1
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2
Incineration of Waste	8.0	12.5	11.3	11.0	10.5	10.4	10.1
Petroleum Systems	4.4	4.9	4.7	4.2	4.5	5.1	6.0
Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.4	4.7	4.0	4.4	4.7
Other Process Uses of Carbonates	4.9	6.3	7.6	9.6	9.3	8.0	4.4
Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Aluminum Production	6.8	4.1	3.0	2.7	3.3	3.4	3.3
Soda Ash Production and Consumption	2.7	2.9	2.5	2.6	2.6	2.7	2.7
Ferroalloy Production	2.2	1.4	1.5	1.7	1.7	1.9	1.8
Titanium Dioxide Production	1.2	1.8	1.6	1.8	1.7	1.5	1.6
Zinc Production	0.6	1.0	0.9	1.2	1.3	1.5	1.4
Phosphoric Acid Production	1.6	1.4	1.0	1.1	1.2	1.1	1.2
Glass Production	1.5	1.9	1.0	1.5	1.3	1.2	1.2
Carbon Dioxide Consumption	1.5	1.4	1.8	1.2	0.8	0.8	0.9
Peatlands Remaining Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.1	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(775.8)*	*(911.9)*	*(870.9)*	*(871.6)*	*(881.0)*	*(880.4)*	*(881.7)*
Wood Biomass and Ethanol Consumption[b]	*219.4*	*229.8*	*250.5*	*265.1*	*268.1*	*267.7*	*283.3*
International Bunker Fuels[c]	*103.5*	*113.1*	*106.4*	*117.0*	*111.7*	*105.8*	*99.8*
CH_4	**745.5**	**707.8**	**709.5**	**667.2**	**660.9**	**647.6**	**636.3**
Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5
Natural Gas Systems	179.1	176.3	168.0	159.6	159.3	154.4	157.4
Landfills	186.2	165.5	158.1	121.8	121.3	115.3	114.6
Coal Mining	96.5	64.1	79.9	82.3	71.2	66.5	64.6
Manure Management	37.2	56.3	59.7	60.9	61.4	63.7	61.4

Petroleum Systems	31.5	23.5	21.5	21.3	22.0	23.3	25.2
Wastewater Treatment	15.7	15.9	15.6	15.5	15.3	15.2	15.0
Rice Cultivation	9.2	8.9	9.4	11.1	8.5	9.3	8.3
Stationary Combustion	8.5	7.4	7.4	7.1	7.1	6.6	8.0
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.6	6.4	6.2	6.2
Forest Fires	2.5	8.3	5.8	4.7	14.6	15.7	5.8
Mobile Combustion	5.6	3.0	2.3	2.3	2.3	2.2	2.1
Composting	0.4	1.9	1.9	1.8	1.9	1.9	2.0
Iron and Steel Production & Metallurgical Coke Production	1.1	0.9	0.4	0.6	0.7	0.7	0.7
Field Burning of Agricultural Residues	0.3	0.2	0.3	0.3	0.3	0.3	0.3
Petrochemical Production	0.2	0.1	+	0.1	+	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[c]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**329.9**	**355.9**	**356.1**	**360.1**	**371.9**	**365.6**	**355.2**
Agricultural Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7
Stationary Combustion	11.9	20.2	20.4	22.2	21.3	21.4	22.9
Mobile Combustion	41.2	38.1	24.6	23.7	22.5	20.2	18.4
Manure Management	13.8	16.4	17.0	17.1	17.3	17.3	17.3
Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7
Wastewater Treatment	3.4	4.3	4.6	4.7	4.8	4.9	4.9
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Adipic Acid Production	15.2	7.1	2.7	4.2	10.2	5.5	4.0
Forest Fires	1.7	5.5	3.8	3.1	9.6	10.3	3.8
Settlement Soils	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Composting	0.3	1.7	1.7	1.6	1.7	1.7	1.8
Forest Soils	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Semiconductor Manufacture	+	0.1	0.1	0.1	0.2	0.2	0.2
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
International Bunker Fuels[c]	*0.9*	*1.0*	*0.9*	*1.0*	*1.0*	*0.9*	*0.9*
HFCs	**46.6**	**131.4**	**142.9**	**152.6**	**157.4**	**159.2**	**163.0**
Substitution of Ozone Depleting Substances[d]	0.3	111.1	136.0	144.4	148.4	153.5	158.6
HCFC-22 Production	46.1	20.0	6.8	8.0	8.8	5.5	4.1
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	0.0	0.0	+	+	+	+	0.1
PFCs	24.3	6.6	3.9	4.4	6.9	6.0	5.8
Aluminum Production	21.5	3.4	1.9	1.9	3.5	2.9	3.0
Semiconductor Manufacture	2.8	3.2	2.0	2.6	3.4	3.0	2.9
SF_6	**31.1**	**14.0**	**9.3**	**9.5**	**10.0**	**7.7**	**6.9**
Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1
Magnesium Production and Processing	5.2	2.7	1.6	2.1	2.8	1.6	1.4
Semiconductor Manufacture	0.5	0.7	0.3	0.4	0.4	0.4	0.4
NF_3	**+**	**0.5**	**0.4**	**0.5**	**0.7**	**0.6**	**0.6**
Semiconductor Manufacture	+	0.5	0.4	0.5	0.7	0.6	0.6
Total Emissions	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**
Total Sinks[a]	**(775.8)**	**(911.9)**	**(870.9)**	**(871.6)**	**(881.0)**	**(880.4)**	**(881.7)**

Net Emissions (Sources and Sinks)	**5,525.2**		**6,438.3**		**5,851.9**	**6,027.2**	**5,895.6**	**5,664.7**	**5,791.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Parentheses indicate negative values or sequestration. Sinks (i.e., CO_2 removals) are only included in the Net Emissions total. Refer to Table 2-8 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

[b] Emissions from Wood Biomass and Ethanol 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 Land Use, Land-Use Change, and Forestry.

[c] Emissions from International Bunker Fuels are not included in totals.

[d] Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

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

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**5,123,695**	**6,133,969**	**5,500,602**	**5,704,531**	**5,568,891**	**5,358,276**	**5,505,178**
Fossil Fuel Combustion	4,740,670	5,747,683	5,197,058	5,367,144	5,231,341	5,026,000	5,157,697
Electricity Generation	1,820,818	2,400,874	2,145,658	2,258,399	2,157,688	2,022,181	2,039,750
Transportation	1,493,758	1,887,799	1,720,314	1,731,971	1,711,538	1,700,782	1,718,406
Industrial	842,473	827,808	727,724	775,674	774,101	784,227	817,252
Residential	338,347	357,827	336,375	334,734	327,211	283,095	329,609
Commercial	217,393	223,453	223,492	220,195	221,022	197,097	220,714
U.S. Territories	27,882	49,923	43,495	46,172	39,781	38,617	31,965
Non-Energy Use of Fuels	117,658	138,877	106,018	114,554	108,359	104,917	119,850
Iron and Steel Production & Metallurgical Coke Production	99,781	66,666	43,029	55,746	60,008	54,327	52,288
Natural Gas Systems	37,645	29,995	32,201	32,334	35,551	34,764	37,808
Cement Production	33,278	45,910	29,432	31,256	32,010	35,051	36,146
Petrochemical Production	21,633	28,124	23,706	27,388	26,396	26,477	26,514
Lime Production	11,700	14,552	11,411	13,381	13,981	13,715	14,072
Ammonia Production	13,047	9,196	8,454	9,188	9,292	9,377	10,152
Incineration of Waste	7,972	12,454	11,295	11,026	10,550	10,363	10,137
Petroleum Systems	4,445	4,904	4,656	4,153	4,467	5,060	6,001
Liming of Agricultural Soils	4,667	4,349	3,669	4,784	3,871	5,776	5,925
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	3,427	4,730	4,029	4,449	4,663
Other Process Uses of Carbonates	4,907	6,339	7,583	9,560	9,335	8,022	4,424
Urea Fertilization	2,417	3,504	3,555	3,778	4,099	4,225	4,011
Aluminum Production	6,831	4,142	3,009	2,722	3,292	3,439	3,255
Soda Ash Production and Consumption	2,741	2,868	2,488	2,612	2,624	2,672	2,712
Ferroalloy Production	2,152	1,392	1,469	1,663	1,735	1,903	1,785
Titanium Dioxide Production	1,195	1,755	1,648	1,769	1,729	1,528	1,608
Zinc Production	632	1,030	943	1,182	1,286	1,486	1,429
Phosphoric Acid Production	1,586	1,395	1,016	1,130	1,198	1,138	1,173
Glass Production	1,535	1,928	1,045	1,481	1,299	1,248	1,160
Carbon Dioxide Consumption	1,472	1,375	1,795	1,206	802	841	903
Peatlands Remaining Peatlands	1,055	1,101	1,024	1,022	926	812	770
Lead Production	516	553	525	542	538	527	525
Silicon Carbide Production and Consumption	375	219	145	181	170	158	169
Magnesium Production and Processing	1	3	1	1	3	2	2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(775,835)*	*(911,929)*	*(870,879)*	*(871,609)*	*(880,999)*	*(880,394)*	*(881,732)*
Wood Biomass and Ethanol Consumption[b]	*219,413*	*229,844*	*250,491*	*265,110*	*268,064*	*267,730*	*283,337*
International Bunker Fuels[c]	*103,463*	*113,139*	*106,410*	*116,992*	*111,660*	*105,805*	*99,763*
CH_4	**29,820**	**28,314**	**28,380**	**26,687**	**26,437**	**25,905**	**25,453**
Enteric Fermentation	6,566	6,755	6,908	6,844	6,750	6,653	6,581
Natural Gas Systems	7,165	7,053	6,722	6,382	6,371	6,176	6,295
Landfills	7,450	6,620	6,324	4,873	4,851	4,611	4,585
Coal Mining	3,860	2,565	3,194	3,293	2,849	2,658	2,584
Manure Management	1,486	2,254	2,388	2,437	2,457	2,548	2,456
Petroleum Systems	1,261	939	860	854	878	931	1,009
Wastewater Treatment	626	635	623	619	610	606	601
Rice Cultivation	366	358	378	444	339	372	332
Stationary Combustion	339	296	295	283	283	264	318

Abandoned Underground Coal Mines	288	264	254	263	257	249	249
Forest Fires	101	332	233	190	584	626	233
Mobile Combustion	225	121	93	92	91	88	86
Composting	15	75	75	73	75	77	79
Iron and Steel Production & Metallurgical Coke Production	46	34	17	25	28	29	28
Field Burning of Agricultural Residues	13	9	12	11	12	12	12
Petrochemical Production	9	6	2	2	2	3	3
Ferroalloy Production	1	+	+	+	+	1	+
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[c]	*7*	*5*	*5*	*6*	*5*	*4*	*3*
N_2O	**1,107**	**1,194**	**1,195**	**1,208**	**1,248**	**1,227**	**1,192**
Agricultural Soil Management	752	817	886	887	892	892	885
Stationary Combustion	40	68	69	74	71	72	77
Mobile Combustion	138	128	82	80	76	68	62
Manure Management	46	55	57	57	58	58	58
Nitric Acid Production	41	38	32	39	37	35	36
Wastewater Treatment	11	15	16	16	16	16	17
N_2O from Product Uses	14	14	14	14	14	14	14
Adipic Acid Production	51	24	9	14	34	19	13
Forest Fires	6	18	13	11	32	35	13
Settlement Soils	5	8	8	8	8	8	8
Composting	1	6	6	5	6	6	6
Forest Soils	+	2	2	2	2	2	2
Incineration of Waste	2	1	1	1	1	1	1
Semiconductor Manufacture	+	+	+	+	1	1	1
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
International Bunker Fuels[c]	*3*	*3*	*3*	*3*	*3*	*3*	*3*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[d]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	1	1	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Aluminum Production	M	M	M	M	M	M	M
Semiconductor Manufacture	M	M	M	M	M	M	M
SF_6	**1**	**+**	**+**	**+**	**+**	**+**	**+**
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+
NF_3	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Semiconductor Manufacture	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M Mixture of multiple gases

[a] Refer to Table 2-8 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

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[b] Emissions from Wood Biomass and Ethanol 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 Land Use, Land-Use Change, and Forestry

[c] Emissions from International Bunker Fuels are not included in totals.

[d] Small amounts of PFC emissions also result from this source.

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

Emissions of all gases can be summed from each source category into a set of five sectors defined by the Intergovernmental Panel on Climate Change (IPCC). Over the twenty four-year period of 1990 to 2013, total emissions in the Energy, Industrial Processes and Product Use, and Agriculture sectors grew by 346.2 MMT CO_2 Eq. (6.5 percent), 17.0 MMT CO_2 Eq. (5.0 percent), and 67.0 MMT CO_2 Eq. (14.9 percent), respectively. Emissions from the Waste sector decreased by 67.7 MMT CO_2 Eq. (32.9 percent). Over the same period, estimates of net C sequestration for the Land Use, Land-Use Change, and Forestry sector increased by 96.4 MMT CO_2 Eq. (12.7 percent).

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

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

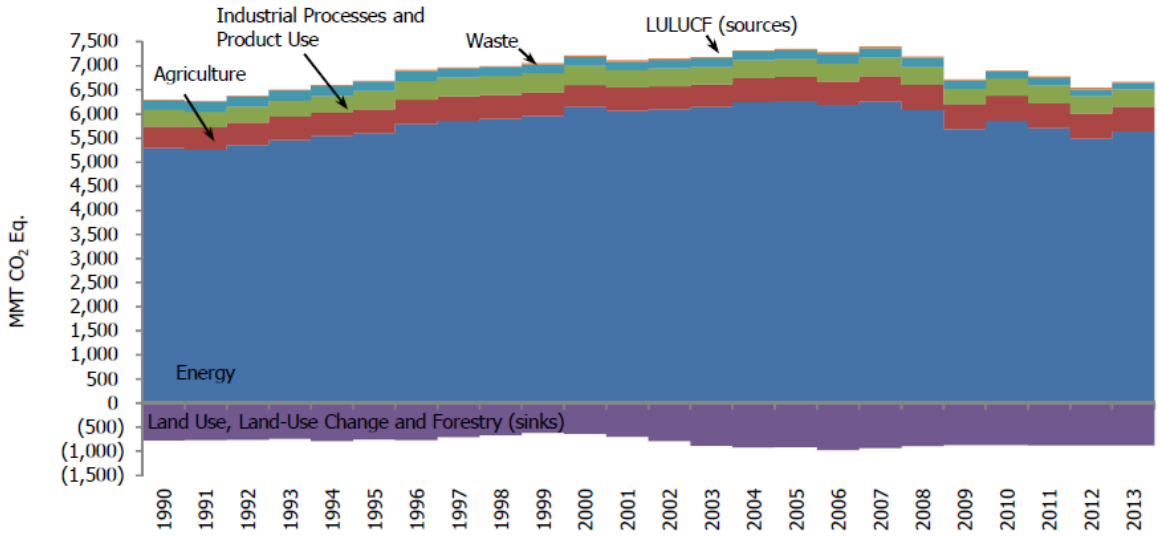


Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO_2 Eq.)

Chapter/IPCC Sector	1990	2005	2009	2010	2011	2012	2013
Energy	**5,290.5**	**6,273.6**	**5,682.1**	**5,854.6**	**5,702.6**	**5,482.2**	**5,636.6**
Fossil Fuel Combustion	4,740.7	5,747.7	5,197.1	5,367.1	5,231.3	5,026.0	5,157.7
Natural Gas Systems	216.8	206.3	200.2	191.9	194.8	189.2	195.2
Non-Energy Use of Fuels	117.7	138.9	106.0	114.6	108.4	104.9	119.8
Coal Mining	96.5	64.1	79.9	82.3	71.2	66.5	64.6
Petroleum Systems	36.0	28.4	26.2	25.5	26.4	28.3	31.2
Stationary Combustion	20.4	27.6	27.8	29.3	28.4	28.0	30.8
Mobile Combustion	46.9	41.1	26.9	26.0	24.8	22.4	20.6
Incineration of Waste	8.4	12.8	11.6	11.4	10.9	10.7	10.4
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.6	6.4	6.2	6.2
Industrial Processes and Product Use	**342.1**	**367.4**	**314.9**	**353.6**	**371.0**	**361.2**	**359.1**
Substitution of Ozone Depleting Substances	0.3	111.1	136.0	144.4	148.4	153.5	158.6
Iron and Steel Production & Metallurgical Coke Production	100.9	67.5	43.5	56.4	60.7	55.1	53.0

Cement Production	33.3	45.9	29.4	31.3	32.0	35.1	36.1
Petrochemical Production	21.9	28.3	23.8	27.4	26.4	26.5	26.6
Lime Production	11.7	14.6	11.4	13.4	14.0	13.7	14.1
Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2
Aluminum Production	28.3	7.6	4.9	4.6	6.8	6.4	6.2
Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.4	4.7	4.0	4.4	4.7
Other Process Uses of Carbonates	4.9	6.3	7.6	9.6	9.3	8.0	4.4
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Semiconductor Manufacture	3.6	4.7	3.1	3.8	4.9	4.5	4.2
HCFC-22 Production	46.1	20.0	6.8	8.0	8.8	5.5	4.1
Adipic Acid Production	15.2	7.1	2.7	4.2	10.2	5.5	4.0
Soda Ash Production and Consumption	2.7	2.9	2.5	2.6	2.6	2.7	2.7
Ferroalloy Production	2.2	1.4	1.5	1.7	1.7	1.9	1.8
Titanium Dioxide Production	1.2	1.8	1.6	1.8	1.7	1.5	1.6
Magnesium Production and Processing	5.2	2.7	1.6	2.1	2.8	1.7	1.5
Zinc Production	0.6	1.0	0.9	1.2	1.3	1.5	1.4
Phosphoric Acid Production	1.6	1.4	1.0	1.1	1.2	1.1	1.2
Glass Production	1.5	1.9	1.0	1.5	1.3	1.2	1.2
Carbon Dioxide Consumption	1.5	1.4	1.8	1.2	0.8	0.8	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**448.7**	**494.5**	**523.3**	**524.8**	**522.1**	**523.0**	**515.7**
Agricultural Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7
Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5
Manure Management	51.0	72.8	76.7	78.0	78.7	81.0	78.7
Rice Cultivation	9.2	8.9	9.4	11.1	8.5	9.3	8.3
Field Burning of Agricultural Residues	0.4	0.3	0.4	0.4	0.4	0.4	0.4
Land Use, Land-Use Change, and Forestry	**13.8**	**25.5**	**20.6**	**20.3**	**36.1**	**39.8**	**23.3**
Forest Fires	4.2	13.8	9.7	7.9	24.2	26.0	9.7
Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Settlement Soils	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Peatlands Remaining Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8
Forest Soils	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Waste	**206.0**	**189.2**	**181.8**	**145.5**	**144.9**	**138.9**	**138.3**
Landfills	186.2	165.5	158.1	121.8	121.3	115.3	114.6
Wastewater Treatment	19.0	20.2	20.2	20.2	20.1	20.0	20.0
Composting	0.7	3.5	3.6	3.5	3.5	3.7	3.7
Total Emissions	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**
Total Sinks[a]	**(775.8)**	**(911.9)**	**(870.9)**	**(871.6)**	**(881.0)**	**(880.4)**	**(881.7)**
Net Emissions (Sources and Sinks)	**5,525.2**	**6,438.3**	**5,851.9**	**6,027.2**	**5,895.6**	**5,664.7**	**5,791.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Sinks (i.e., CO_2 removals) are only included in the Net Emissions total. Refer to Table 2-8 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

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

Energy

Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2013. In 2013, approximately 82 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 18 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure 2-5 and Figure 2-6). A discussion of specific trends related to CO_2 as well as other greenhouse gas emissions from energy consumption is presented in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (41 percent and 12 percent of total U.S. emissions of each gas, respectively). Table 2-4 presents greenhouse gas emissions from the Energy chapter, by source and gas.

Figure 2-5: 2013 Energy Chapter Greenhouse Gas Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

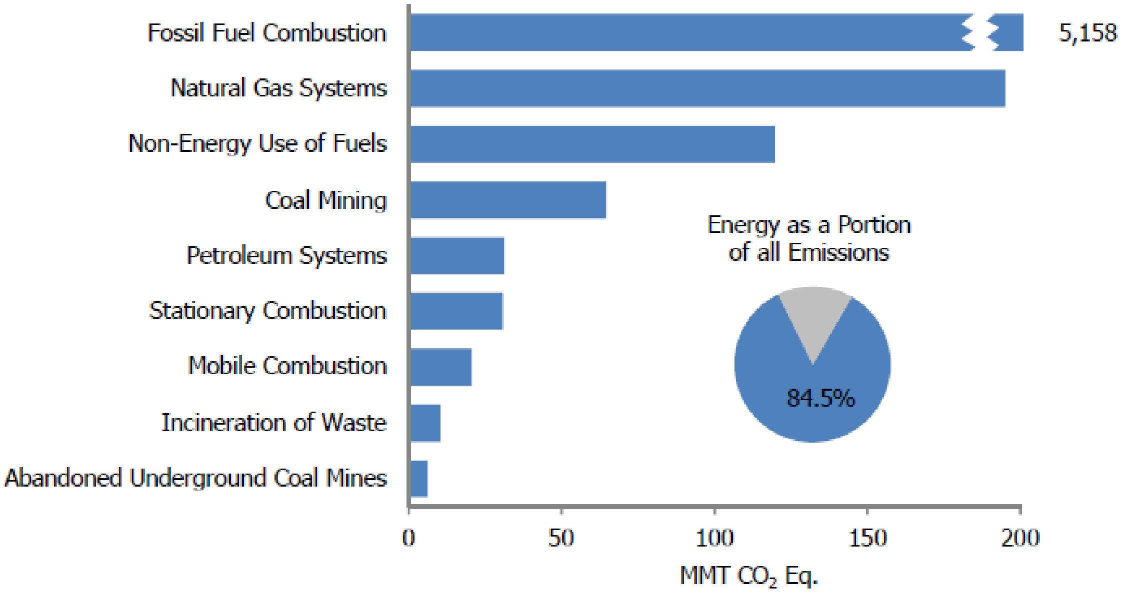
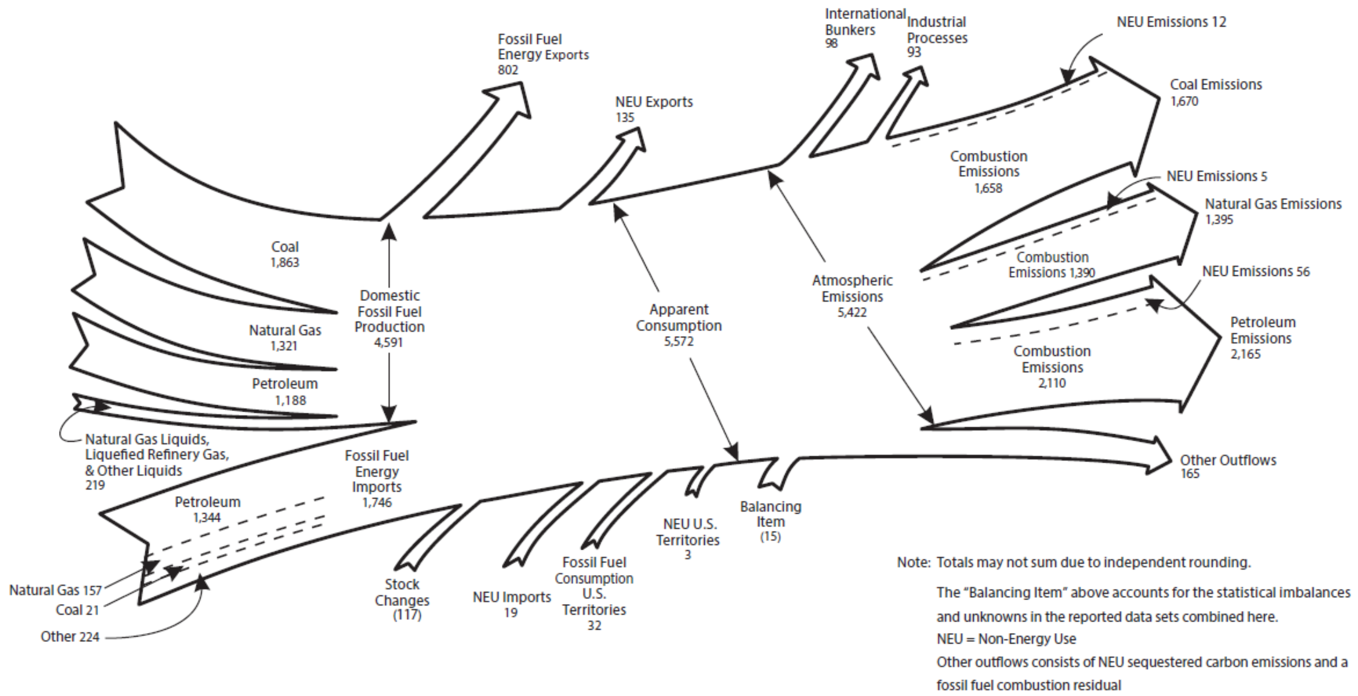


Figure 2-6: 2013 U.S. Fossil Carbon Flows (MMT CO_2 Eq.)

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Note: Totals may not sum due to independent rounding.

The "Balancing Item" above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

NEU = Non-Energy Use

Other outflows consists of NEU sequestered carbon emissions and a fossil fuel combustion residual

Table 2-4: Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**4,908.4**	**5,933.9**	**5,351.2**	**5,529.2**	**5,390.3**	**5,181.1**	**5,331.5**
Fossil Fuel Combustion	4,740.7	5,747.7	5,197.1	5,367.1	5,231.3	5,026.0	5,157.7
Electricity Generation	1,820.8	2,400.9	2,145.7	2,258.4	2,157.7	2,022.2	2,039.8
Transportation	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4
Industrial	842.5	827.8	727.7	775.7	774.1	784.2	817.3
Residential	338.3	357.8	336.4	334.7	327.2	283.1	329.6
Commercial	217.4	223.5	223.5	220.2	221.0	197.1	220.7
U.S. Territories	27.9	49.9	43.5	46.2	39.8	38.6	32.0
Non-Energy Use of Fuels	117.7	138.9	106.0	114.6	108.4	104.9	119.8
Natural Gas Systems	37.6	30.0	32.2	32.3	35.6	34.8	37.8
Incineration of Waste	8.0	12.5	11.3	11.0	10.5	10.4	10.1
Petroleum Systems	4.4	4.9	4.7	4.2	4.5	5.1	6.0
Biomass - Wood[a]	*215.2*	*206.9*	*188.2*	*192.5*	*195.2*	*194.9*	*208.6*
International Bunker Fuels[b]	*103.5*	*113.1*	*106.4*	*117.0*	*111.7*	*105.8*	*99.8*
Biomass - Ethanol[a]	*4.2*	*22.9*	*62.3*	*72.6*	*72.9*	*72.8*	*74.7*
CH_4	**328.5**	**280.9**	**285.5**	**279.2**	**268.2**	**259.2**	**263.5**
Natural Gas Systems	179.1	176.3	168.0	159.6	159.3	154.4	157.4
Coal Mining	96.5	64.1	79.9	82.3	71.2	66.5	64.6
Petroleum Systems	31.5	23.5	21.5	21.3	22.0	23.3	25.2
Stationary Combustion	8.5	7.4	7.4	7.1	7.1	6.6	8.0
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.6	6.4	6.2	6.2
Mobile Combustion	5.6	3.0	2.3	2.3	2.3	2.2	2.1
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**53.6**	**58.7**	**45.3**	**46.2**	**44.1**	**41.9**	**41.6**
Stationary Combustion	11.9	20.2	20.4	22.2	21.3	21.4	22.9
Mobile Combustion	41.2	38.1	24.6	23.7	22.5	20.2	18.4

Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
International Bunker Fuels[b]	*0.9*	*1.0*	*0.9*	*1.0*	*1.0*	*0.9*	*0.9*
Total	**5,290.5**	**6,273.6**	**5,682.1**	**5,854.6**	**5,702.6**	**5,482.2**	**5,636.6**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass and Ethanol 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 Land Use, Land-Use Change, and Forestry.

[b] Emissions from International Bunker Fuels are not included in totals.

Carbon dioxide emissions from fossil fuel combustion are presented in Table 2-5 based on the underlying U.S. energy consumer data collected by EIA. Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA "end-use sectors" based on total consumption and appropriate fuel properties (any additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report). EIA's fuel consumption data for the electric power sector comprises electricity-only and combined-heat-and-power (CHP) plants within the NAICS 22 category whose primary business is to sell electricity, or electricity and heat, to the public (nonutility power producers can be included in this sector as long as they meet they electric power sector definition). 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 transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another. EIA's fuel consumption data for the industrial sector consists 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). EIA's fuel consumption data for the residential sector consists of living quarters for private households. EIA's fuel consumption data for the commercial sector consists 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 and Figure 2-7 summarize CO_2 emissions from fossil fuel combustion by end-use sector. Figure 2-8 further describes the total emissions from fossil fuel combustion, separated by end-use sector, including CH_4 and N_2O in addition to CO_2.

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

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Transportation	**1,496.8**	**1,892.5**	**1,724.8**	**1,736.5**	**1,715.8**	**1,704.6**	**1,722.4**
Combustion	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4
Electricity	3.0	4.7	4.5	4.5	4.3	3.9	4.0
Industrial	**1,529.2**	**1,564.4**	**1,329.5**	**1,416.5**	**1,398.8**	**1,377.0**	**1,399.8**
Combustion	842.5	827.8	727.7	775.7	774.1	784.2	817.3
Electricity	686.7	736.6	601.8	640.8	624.7	592.8	582.5
Residential	**931.4**	**1,214.1**	**1,122.6**	**1,174.8**	**1,117.9**	**1,008.4**	**1,070.2**
Combustion	338.3	357.8	336.4	334.7	327.2	283.1	329.6
Electricity	593.0	856.3	786.2	840.1	790.7	725.3	740.6
Commercial	**755.4**	**1,026.7**	**976.7**	**993.2**	**959.1**	**897.4**	**933.3**
Combustion	217.4	223.5	223.5	220.2	221.0	197.1	220.7
Electricity	538.0	803.3	753.2	773.0	738.0	700.3	712.6
U.S. Territories[a]	**27.9**	**49.9**	**43.5**	**46.2**	**39.8**	**38.6**	**32.0**
Total	**4,740.7**	**5,747.7**	**5,197.1**	**5,367.1**	**5,231.3**	**5,026.0**	**5,157.7**
Electricity Generation	**1,820.8**	**2,400.9**	**2,145.7**	**2,258.4**	**2,157.7**	**2,022.2**	**2,039.8**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

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

[a] 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.

Figure 2-7: 2013 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

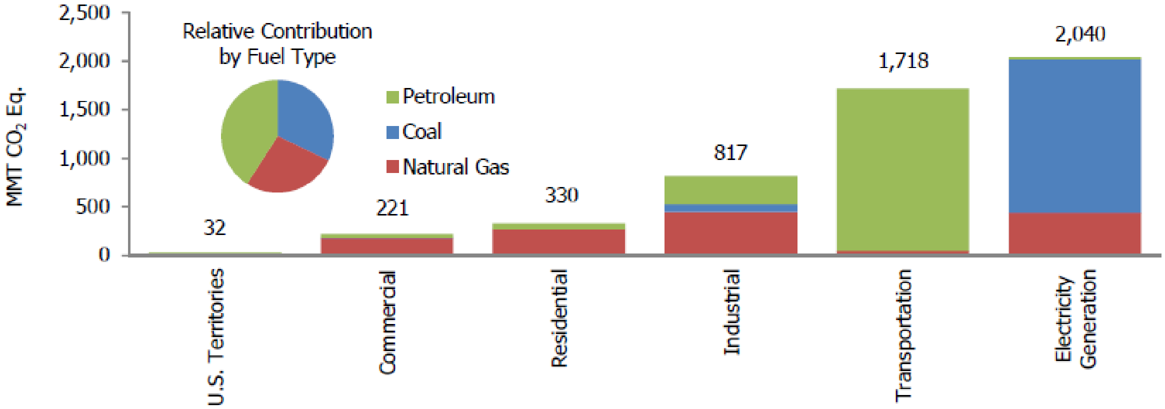
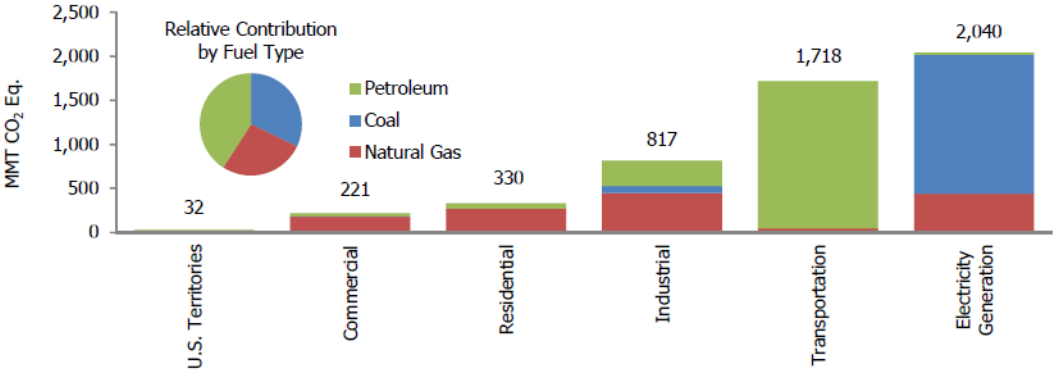


Figure 2-8: 2013 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



The main driver of emissions in the Energy sector is CO_2 from fossil fuel combustion. Electricity generation is the largest emitter of CO_2, and electricity generators consumed 34 percent of U.S. energy from fossil fuels and emitted 40 percent of the CO_2 from fossil fuel combustion in 2013. Electricity generation emissions can also be allocated to the end-use sectors that are consuming that electricity, as presented in Table 2-5. The transportation end-use sector accounted for 1,722.4 MMT CO_2 Eq. in 2013 or approximately 33 percent of total CO_2 emissions from fossil fuel combustion. The industrial end-use sector accounted for 27 percent of CO_2 emissions from fossil fuel combustion. The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both of these end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing 69 and 76 percent of emissions from the residential and commercial end-use sectors, respectively. Significant trends in emissions from energy source categories over the twenty four-year period from 1990 through 2013 included the following:

- Total CO_2 emissions from fossil fuel combustion increased from 4,740.7 MMT CO_2 Eq. in 1990 to 5,157.7 MMT CO_2 Eq. in 2013 – an 8.8 percent total increase over the twenty four-year period. From 2012 to 2013, these emissions increased by 131.7 MMT CO_2 Eq. (2.6 percent).
- CH_4 emissions from natural gas systems were the second largest anthropogenic source of CH_4 emissions in the United States with 157.4 MMT CO_2 Eq. emitted into the atmosphere in 2013; emissions have decreased by 21.8 MMT CO_2 Eq. (12.2 percent) since 1990.

- CO_2 emissions from non-energy use of fossil fuels increased by 2.2 MMT CO_2 Eq. (1.9 percent) from 1990 through 2013. Emissions from non-energy uses of fossil fuels were 119.8 MMT CO_2 Eq. in 2013, which constituted 2.2 percent of total national CO_2 emissions.
- N_2O emissions from stationary combustion increased by 11.0 MMT CO_2 Eq. (91.9 percent) from 1990 through 2013. N_2O emissions from this source increased primarily as a result of an increase in the number of coal fluidized bed boilers in the electric power sector.
- CO_2 emissions from incineration of waste (10.1 MMT CO_2 Eq. in 2013) increased by 2.2 MMT CO_2 Eq. (27.2 percent) from 1990 through 2013, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.

The increase in CO_2 emissions from fossil fuel combustion in 2013 was a result of multiple factors including: (1) the increase in the price of natural gas led to an increase of coal-fired generation in the electric power sector; (2) much colder winter conditions resulted in an increased demand for heating fuel in the residential and commercial sectors; (3) an increase in industrial production across multiple sectors which resulted in increases in industrial sector emissions,[1] and (4) an increase in transportation emissions resulting from a small increase in vehicle miles traveled (VMT) and fuel use across on-road transportation modes.

Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. This section includes sources of emissions formerly represented in the "Industrial Processes" and "Solvent and Other Product Use" sectors in prior versions of this report.

Greenhouse gas emissions are produced as the by-products of many non-energy-related industrial activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2, CH_4, and N_2O. These processes include iron and steel production and metallurgical coke production, cement production, ammonia production, urea consumption, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and consumption, titanium dioxide production, phosphoric acid production, ferroalloy production, CO_2 consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, zinc production, and N_2O from product uses (see Figure 2-9). Industrial processes also release HFCs, PFCs, SF_6, and NF_3. In addition to their use as ODS substitutes, HFCs, PFCs, SF_6, NF_3, and other fluorinated compounds are employed and emitted by a number of other industrial sources in the United States. These industries include aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. Table 2-6 presents greenhouse gas emissions from industrial processes by source category.

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

Figure 2-9: 2013 Industrial Processes and Product Use Chapter Greenhouse Gas Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

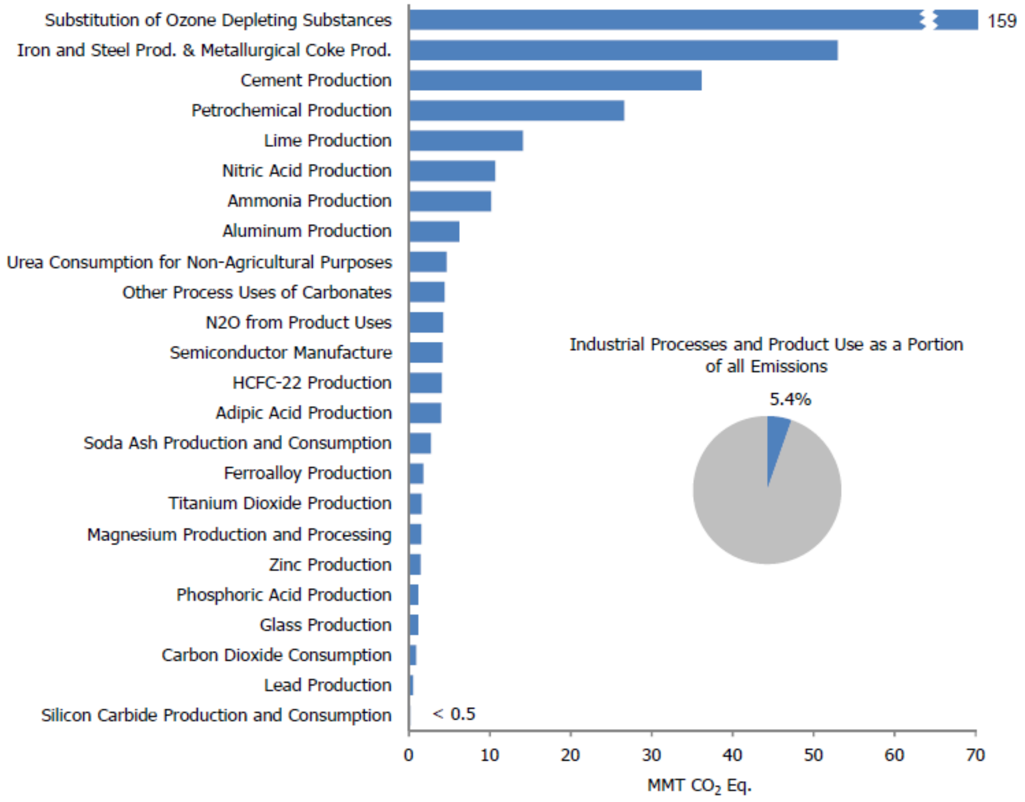

Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**207.2**	**191.1**	**141.1**	**165.7**	**169.7**	**166.4**	**163.0**
Iron and Steel Production & Metallurgical Coke Production	99.8	66.7	43.0	55.7	60.0	54.3	52.3
Iron and Steel Production	*97.3*	*64.6*	*42.1*	*53.7*	*58.6*	*53.8*	*50.5*
Metallurgical Coke Production	*2.5*	*2.0*	*1.0*	*2.1*	*1.4*	*0.5*	*1.8*
Cement Production	33.3	45.9	29.4	31.3	32.0	35.1	36.1
Petrochemical Production	21.6	28.1	23.7	27.4	26.4	26.5	26.5
Lime Production	11.7	14.6	11.4	13.4	14.0	13.7	14.1
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.4	4.7	4.0	4.4	4.7
Other Process Uses of Carbonates	4.9	6.3	7.6	9.6	9.3	8.0	4.4
Aluminum Production	6.8	4.1	3.0	2.7	3.3	3.4	3.3
Soda Ash Production and Consumption	2.7	2.9	2.5	2.6	2.6	2.7	2.7
Ferroalloy Production	2.2	1.4	1.5	1.7	1.7	1.9	1.8
Titanium Dioxide Production	1.2	1.8	1.6	1.8	1.7	1.5	1.6
Zinc Production	0.6	1.0	0.9	1.2	1.3	1.5	1.4
Phosphoric Acid Production	1.6	1.4	1.0	1.1	1.2	1.1	1.2
Glass Production	1.5	1.9	1.0	1.5	1.3	1.2	1.2
Carbon Dioxide Consumption	1.5	1.4	1.8	1.2	0.8	0.8	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.1	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
CH_4	**1.4**	**1.0**	**0.5**	**0.7**	**0.8**	**0.8**	**0.8**

Iron and Steel Production & Metallurgical Coke Production	1.1	0.9	0.4	0.6	0.7	0.7	0.7
Iron and Steel Production	*1.1*	*0.9*	*0.4*	*0.6*	*0.7*	*0.7*	*0.7*
Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	0.2	0.1	+	0.1	+	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
N_2O	**31.6**	**22.8**	**16.7**	**20.1**	**25.5**	**20.4**	**19.1**
Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Adipic Acid Production	15.2	7.1	2.7	4.2	10.2	5.5	4.0
Semiconductor Manufacturing	+	0.1	0.1	0.1	0.2	0.2	0.2
HFCs	**46.6**	**131.4**	**142.9**	**152.6**	**157.4**	**159.2**	**163.0**
Substitution of Ozone Depleting Substances[a]	0.3	111.1	136.0	144.4	148.4	153.5	158.6
HCFC-22 Production	46.1	20.0	6.8	8.0	8.8	5.5	4.1
Semiconductor Manufacturing	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	0	+	+	+	+	+	0.1
PFCs	**24.3**	**6.6**	**3.9**	**4.4**	**6.9**	**6.0**	**5.8**
Aluminum Production	21.5	3.4	1.9	1.9	3.5	2.9	3.0
Semiconductor Manufacturing	2.8	3.2	2.0	2.6	3.4	3.0	2.9
SF_6	**31.1**	**14.0**	**9.3**	**9.5**	**10.0**	**7.7**	**6.9**
Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1
Magnesium Production and Processing	5.2	2.7	1.6	2.1	2.8	1.6	1.4
Semiconductor Manufacturing	0.5	0.7	0.3	0.4	0.4	0.4	0.4
NF_3	**+**	**0.5**	**0.4**	**0.5**	**0.7**	**0.6**	**0.6**
Semiconductor Manufacturing	+	0.5	0.4	0.5	0.7	0.6	0.6
Total	**342.1**	**367.4**	**314.9**	**353.6**	**371.0**	**361.2**	**359.1**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

Overall, emissions from the IPPU sector increased by 5.0 percent from 1990 to 2013. Significant trends in emissions from IPPU source categories over the twenty four-year period from 1990 through 2013 included the following:

- HFC emissions from ODS substitutes have been increasing from small amounts in 1990 to 158.6 MMT CO_2 Eq. in 2013. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*.
- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production decreased by 3.8 percent to 53.0 MMT CO_2 Eq. from 2012 to 2013, and have declined overall by 47.9 MMT CO_2 Eq. (47.5 percent) from 1990 through 2013, due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- CO_2 emissions from ammonia production (10.2 MMT CO_2 Eq. in 2013) decreased by 2.9 MMT CO_2 Eq. (22.2 percent) 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.
- Urea consumption for non-agricultural purposes (4.7 MMT CO_2 Eq. in 2013) increased by 0.9 MMT CO_2 Eq. (23.2 percent) since 1990.
- In 2013, N_2O emissions from product uses constituted 1.2 percent of U.S. N_2O emissions. From 1990 to 2013, emissions from this source category decreased by 0.4 percent, though slight increases occurred in intermediate years.

- N_2O emissions from adipic acid production were 4.0 MMT CO_2 Eq. in 2013, and have decreased significantly since 1990 due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. Emissions from adipic acid production have decreased by 73.8 percent since 1990 and by 76.4 percent since a peak in 1995.
- PFC emissions from aluminum production decreased by 86.2 percent (18.5 MMT CO_2 Eq.) from 1990 to 2013, due to both industry emission reduction efforts and lower domestic aluminum production.

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, and field burning of agricultural residues.

In 2013, agricultural activities were responsible for emissions of 515.7 MMT CO_2 Eq., or 7.7 percent of total U.S. greenhouse gas emissions. CH_4 and N_2O were the primary greenhouse gases emitted by agricultural activities. CH_4 emissions from enteric fermentation and manure management represented about 25.9 percent and 9.6 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2013. Agricultural soil management activities, such as fertilizer use and other cropping practices, were the largest source of U.S. N_2O emissions in 2013, accounting for 74.2 percent.

Figure 2-10: 2013 Agriculture Chapter Greenhouse Gas Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

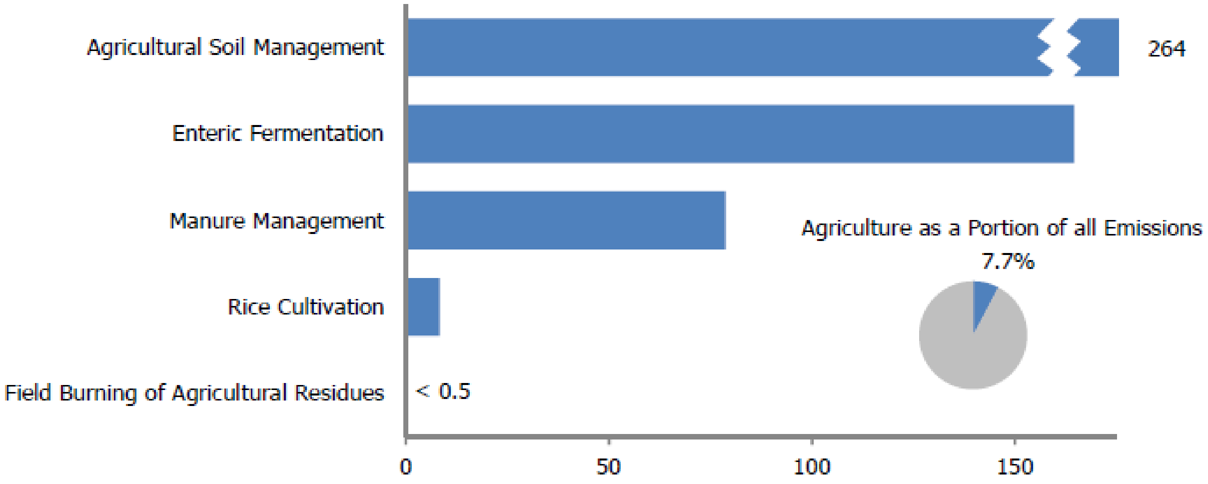

Table 2-7: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CH_4	**210.8**	**234.4**	**242.1**	**243.4**	**238.9**	**239.6**	**234.5**
Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5
Manure Management	37.2	56.3	59.7	60.9	61.4	63.7	61.4
Rice Cultivation	9.2	8.9	9.4	11.1	8.5	9.3	8.3
Field Burning of Agricultural Residues	0.3	0.2	0.3	0.3	0.3	0.3	0.3
N_2O	**237.9**	**260.1**	**281.2**	**281.4**	**283.2**	**283.4**	**281.1**
Agricultural Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7
Manure Management	13.8	16.4	17.0	17.1	17.3	17.3	17.3
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**448.7**	**494.5**	**523.3**	**524.8**	**522.1**	**523.0**	**515.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from Agriculture source categories include the following:

- Agricultural soils produced approximately 74.2 percent of N_2O emissions in the United States in 2013. Estimated emissions from this source in 2013 were 263.7 MMT CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2013, although overall emissions were 17.7 percent higher in 2013 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 2013, enteric fermentation CH_4 emissions were 164.5 MMT CO_2 Eq. (25.9 percent of total CH_4 emissions), which represents an increase of 0.4 MMT CO_2 Eq. (0.2 percent) since 1990. This increase in emissions from 1990 to 2013 in enteric generally follows the increasing trends in cattle populations. 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 underwent increases and the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again from 2008 to 2013 as beef cattle populations again decreased.
- Overall, emissions from manure management increased 54.4 percent between 1990 and 2013. This encompassed an increase of 65.2 percent for CH_4, from 37.2 MMT CO_2 Eq. in 1990 to 61.4 MMT CO_2 Eq. in 2013; and an increase of 25.4 percent for N_2O, from 13.8 MMT CO_2 Eq. in 1990 to 17.3 MMT CO_2 Eq. in 2013. The majority of the increase observed in CH_4 resulted from swine and dairy cow manure, where emissions increased 48 and 115 percent, respectively, from 1990 to 2013. From 2012 to 2013, there was a 3.6 percent decrease in total CH_4 emissions from manure management, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

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 alter the background carbon fluxes between biomass, soils, and the atmosphere. Forest management practices, tree planting in urban areas, the management of agricultural soils, and the landfilling of yard trimmings and food scraps have resulted in a net removal of CO_2 (sequestration of C) in the United States. Forests (including vegetation, soils, and harvested wood) accounted for approximately 88 percent of total 2013 CO_2 removals, urban trees accounted for 10 percent, mineral and organic soil carbon stock changes accounted for less than 0.5 percent, and landfilled yard trimmings and food scraps accounted for 1.4 percent of total CO_2 removals in 2013. The net forest sequestration is a result of net forest growth, increasing forest area, and a net accumulation of carbon stocks in harvested wood pools. The net sequestration in urban forests is a result of net tree growth and increased urban forest size. In agricultural soils, mineral and organic soils sequester approximately 2.4 times as much C as is emitted from these soils through liming and urea fertilization. The mineral soil C sequestration is largely due to the conversion of cropland to hay production fields, the limited use of bare-summer fallow areas in semi-arid areas, and an increase in the adoption of conservation tillage practices. The landfilled yard trimmings and food scraps net sequestration is due to the long-term accumulation of yard trimming and food scraps carbon in landfills.

Land use, land-use change, and forestry activities in 2013 resulted in a C sequestration (i.e., total sinks) of 881.7 MMT CO_2 Eq. (Table 2-3).[2] This represents an offset of approximately 13.2 percent of total (i.e., gross) greenhouse gas emissions in 2013. Emissions from land use, land-use change and forestry activities in 2013 represent 0.3 percent of total greenhouse gas emissions.[3] Between 1990 and 2013, total land use, land-use change, and forestry C sequestration increased by 13.6 percent, primarily due to an increase in the rate of net C accumulation in forest C stocks, particularly in aboveground and belowground tree biomass, and harvested wood pools.

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[2] The total sinks value includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland*.

[3] The emissions value includes the CO_2, CH_4, and N_2O emissions reported for *Forest Fires, Forest Soils, Liming of Agricultural Soils, Urea Fertilization, Settlement Soils,* and *Peatlands Remaining Peatlands*.

CO_2 removals are presented in Table 2-8 along with CO_2, CH_4, and N_2O emissions for Land Use, Land-Use Change, and Forestry source categories. Liming of agricultural soils and urea fertilization resulted in CO_2 emissions of 9.9 MMT CO_2 Eq. in 2013, an increase of about 40.3 percent relative to 1990. Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO_2 emissions of 0.8 MMT CO_2 Eq. and CH_4 and N_2O emissions of less than 0.05 MMT CO_2 Eq. each. N_2O emissions from the application of synthetic fertilizers to forest soils have increased from 0.1 MMT CO_2 Eq. in 1990 to 0.5 MMT CO_2 Eq. in 2013. Settlement soils in 2013 resulted in N_2O emissions of 2.4 MMT CO_2 Eq., a 76.7 percent increase relative to 1990. Emissions from forest fires in 2013 resulted in CH_4 emissions of 5.8 MMT CO_2 and in N_2O emissions of 3.8 MMT CO_2 (see Table 2-8).

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

Gas/Land-Use Category	1990	2005	2009	2010	2011	2012	2013
CO_2	**(767.7)**	**(903.0)**	**(862.6)**	**(862.0)**	**(872.1)**	**(869.6)**	**(871.0)**
Forest Land Remaining Forest Land: Changes in Forest Carbon Stock[a]	(639.4)	(807.1)	(764.9)	(765.4)	(773.8)	(773.1)	(775.7)
Cropland Remaining Cropland: Changes in Agricultural Soil Carbon Stock	(65.2)	(28.0)	(27.5)	(25.9)	(25.8)	(25.0)	(23.4)
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Cropland Remaining Cropland: Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Land Converted to Cropland	24.5	19.8	16.2	16.2	16.2	16.1	16.1
Grassland Remaining Grassland	(1.9)	4.2	11.7	11.7	11.7	11.5	12.1
Land Converted to Grassland	(7.4)	(9.0)	(8.9)	(8.9)	(8.9)	(8.8)	(8.8)
Settlements Remaining Settlements: Changes in Urban Tree Carbon Stock[b]	(60.4)	(80.5)	(85.0)	(86.1)	(87.3)	(88.4)	(89.5)
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.1	1.0	1.0	0.9	0.8	0.8
Other: Landfilled Yard Trimmings and Food Scraps	(24.2)	(12.0)	(12.9)	(13.6)	(13.5)	(13.0)	(12.8)
CH_4	**2.5**	**8.3**	**5.8**	**4.8**	**14.6**	**15.7**	**5.8**
Forest Land Remaining Forest Land: Forest Fires	2.5	8.3	5.8	4.7	14.6	15.7	5.8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.1**	**8.3**	**6.5**	**6.0**	**12.6**	**13.3**	**6.7**
Forest Land Remaining Forest Land: Forest Fires	1.7	5.5	3.8	3.1	9.6	10.3	3.8
Forest Land Remaining Forest Land: Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Settlements Remaining Settlements: Settlement Soils[d]	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total Flux [e]	**(762.1)**	**(886.4)**	**(850.2)**	**(851.3)**	**(844.9)**	**(840.6)**	**(858.5)**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Less than 0.05 MMT CO_2 Eq.

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[d] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

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[e] "Total Flux" is defined as the sum of positive emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.
Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Other significant trends from 1990 to 2013 in emissions from land use, land-use change, and forestry source categories include:

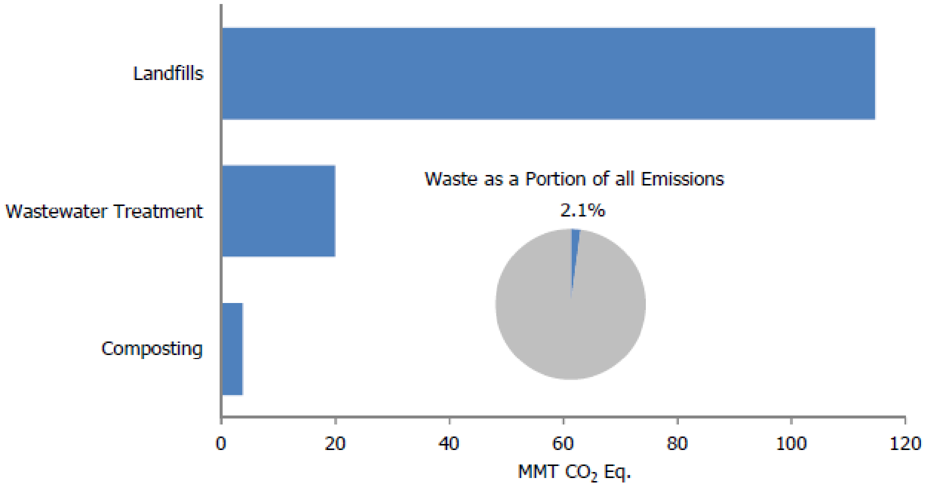
- Annual C sequestration by forest land (i.e., annual carbon stock accumulation in the five carbon pools) has increased by approximately 21 percent. This is primarily due to increased forest management and the effects of previous reforestation. The increase in intensive forest management resulted in higher growth rates and higher biomass density. The tree planting and conservation efforts of the 1970s and 1980s continue to have a significant impact on sequestration rates. Finally, the forested area in the United States increased over the past twenty four-years, although only at an average rate of 0.1 percent per year.
- Annual C sequestration by urban trees has increased by 48.1 percent over the period from 1990 to 2013. This is primarily due to an increase in urbanized land area in the United States.
- Annual C sequestration in landfilled yard trimmings and food scraps has decreased by 51.6 percent since 1990. Food scrap generation has grown by 53 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 78 percent in 2013, the tonnage disposed in landfills has increased considerably (by 46 percent). Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-11). In 2013, landfills were the third largest source of U.S. anthropogenic CH_4 emissions, accounting for 18.0 percent of total U.S. CH_4 emissions.[4] Additionally, wastewater treatment accounts for 14.4 percent of Waste emissions, 2.4 percent of U.S. CH_4 emissions, and 1.4 percent of N_2O emissions. Emissions of CH_4 and N_2O from composting grew from 1990 to 2013, and resulted in emissions of 3.7 MMT CO_2 Eq. in 2013. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-9.

Figure 2-11: 2013 Waste Chapter Greenhouse Gas Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



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[4] 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.

Overall, in 2013, waste activities generated emissions of 138.3 MMT CO_2 Eq., or 2.1 percent of total U.S. greenhouse gas emissions.

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

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CH_4	**202.3**	**183.2**	**175.5**	**139.1**	**138.4**	**132.4**	**131.6**
Landfills	186.2	165.5	158.1	121.8	121.3	115.3	114.6
Wastewater Treatment	15.7	15.9	15.6	15.5	15.3	15.2	15.0
Composting	0.4	1.9	1.9	1.8	1.9	1.9	2.0
N_2O	**3.7**	**6.0**	**6.3**	**6.4**	**6.5**	**6.6**	**6.7**
Wastewater Treatment	3.4	4.3	4.6	4.7	4.8	4.9	4.9
Composting	0.3	1.7	1.7	1.6	1.7	1.7	1.8
Total	**206.0**	**189.2**	**181.8**	**145.5**	**144.9**	**138.9**	**138.3**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from waste source categories include the following:

- From 1990 to 2013, net CH_4 emissions from landfills decreased by 71.6 MMT CO_2 Eq. (38.4 percent), with small increases occurring in interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted as well as reduction in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series,[5] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.
- Combined CH_4 and N_2O emissions from composting have generally increased since 1990, from 0.7 MMT CO_2 Eq. to 3.7 MMT CO_2 Eq. in 2013, which represents slightly more than a five-fold increase over the time series. The growth in composting since the 1990s is attributable to primarily two factors: (1) steady growth in population and residential housing, and (2) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills.
- From 1990 to 2013, CH_4 and N_2O emissions from wastewater treatment decreased by 0.6 MMT CO_2 Eq. (4.0 percent) and increased by 1.6 MMT CO_2 Eq. (46.5 percent), 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. Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

2.1 Emissions by Economic Sector

Throughout this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC and detailed above: Energy; Industrial Processes; Solvent and Other Product Use; Agriculture; Land Use, Land-Use Change, and Forestry; and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines, it is also useful to allocate emissions into more commonly used sectoral categories. This section reports emissions by the following U.S. economic sectors: residential, commercial, industry, transportation, electricity generation, and agriculture, as well as U.S. Territories.

Using this categorization, emissions from electricity generation accounted for the largest portion (31 percent) of U.S. greenhouse gas emissions in 2013. Transportation activities, in aggregate, accounted for the second largest portion (27 percent). Emissions from industry accounted for about 21 percent of U.S. greenhouse gas emissions in

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[5] The CO_2 produced from combusted landfill CH_4 at landfills is not counted in national inventories as it is considered part of the natural C cycle of decomposition.

2013. In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade. The long-term decline in these emissions has been 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. The remaining 21 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, and commercial sectors, plus emissions from U.S. Territories. The residential sector accounted for 6 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 9 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, rather than CO_2 from fossil fuel combustion. The commercial sector accounted for roughly 6 percent of emissions, while U.S. territories accounted for less than 1 percent. Carbon dioxide was also emitted and sequestered (in the form of C) by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, and landfilling of yard trimmings.

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 2-12 shows the trend in emissions by sector from 1990 to 2013.

Figure 2-12: Emissions Allocated to Economic Sectors

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

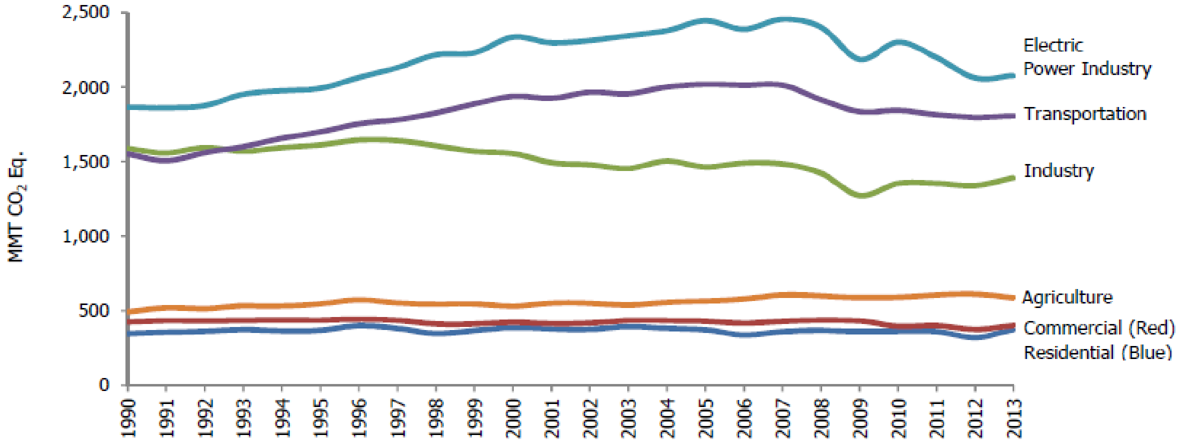


Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq. and Percent of Total in 2013)

Sector/Source	1990	2005	2009	2010	2011	2012	2013	Percent[a]
Electric Power Industry	**1,864.8**	**2,443.9**	**2,185.7**	**2,300.5**	**2,198.1**	**2,060.8**	**2,077.0**	**31.1%**
CO_2 from Fossil Fuel Combustion	1,820.8	2,400.9	2,145.7	2,258.4	2,157.7	2,022.2	2,039.8	30.6%
Stationary Combustion	7.7	16.5	17.2	18.9	18.0	18.2	19.5	0.3%
Incineration of Waste	8.4	12.8	11.6	11.4	10.9	10.7	10.4	0.2%
Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1	0.1%
Other Process Uses of Carbonates	2.5	3.2	3.8	4.8	4.7	4.0	2.2	+
Transportation	**1,551.3**	**2,017.7**	**1,835.3**	**1,843.5**	**1,815.4**	**1,795.9**	**1,806.2**	**27.1%**
CO_2 from Fossil Fuel Combustion	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4	25.8%
Substitution of Ozone Depleting Substances	+	80.4	81.4	77.9	72.0	66.3	60.5	0.9%
Mobile Combustion	45.7	39.4	25.1	24.1	22.9	20.5	18.6	0.3%
Non-Energy Use of Fuels	11.8	10.2	8.5	9.5	9.0	8.3	8.8	0.1%
Industry	**1,587.7**	**1,462.8**	**1,272.5**	**1,353.3**	**1,353.0**	**1,338.9**	**1,392.1**	**20.9%**
CO_2 from Fossil Fuel Combustion	811.4	781.0	681.2	728.2	724.9	733.5	767.6	11.5%
Natural Gas Systems	216.8	206.3	200.2	191.9	194.8	189.2	195.2	2.9%
Non-Energy Use of Fuels	100.1	120.6	93.5	100.9	95.8	93.3	108.4	1.6%

Coal Mining	96.5	64.1	79.9	82.3	71.2	66.5	64.6	1.0%
Iron and Steel Production	100.9	67.5	43.5	56.4	60.7	55.1	53.0	0.8%
Cement Production	33.3	45.9	29.4	31.3	32.0	35.1	36.1	0.5%
Petroleum Systems	36.0	28.4	26.2	25.5	26.4	28.3	31.2	0.5%
Petrochemical Production	21.9	28.3	23.8	27.4	26.4	26.5	26.6	0.4%
Substitution of Ozone Depleting Substances	+	7.3	12.4	15.3	17.0	18.7	20.4	0.3%
Lime Production	11.7	14.6	11.4	13.4	14.0	13.7	14.1	0.2%
Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7	0.2%
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2	0.2%
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.6	6.4	6.2	6.2	0.1%
Aluminum Production	28.3	7.6	4.9	4.6	6.8	6.4	6.2	0.1%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.4	4.7	4.0	4.4	4.7	0.1%
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2	0.1%
Semiconductor Manufacture	3.6	4.7	3.1	3.8	4.9	4.5	4.2	0.1%
HCFC-22 Production	46.1	20.0	6.8	8.0	8.8	5.5	4.1	0.1%
Adipic Acid Production	15.2	7.1	2.7	4.2	10.2	5.5	4.0	0.1%
Stationary Combustion	4.9	4.6	3.6	3.9	3.9	3.9	3.9	0.1%
Soda Ash Production and Consumption	2.7	2.9	2.5	2.6	2.6	2.7	2.7	+
Other Process Uses of Carbonates	2.5	3.2	3.8	4.8	4.7	4.0	2.2	+
Ferroalloy Production	2.2	1.4	1.5	1.7	1.7	1.9	1.8	+
Titanium Dioxide Production	1.2	1.8	1.6	1.8	1.7	1.5	1.6	+
Magnesium Production and Processing	5.2	2.7	1.6	2.1	2.8	1.7	1.5	+
Mobile Combustion	0.9	1.3	1.3	1.4	1.4	1.4	1.5	+
Zinc Production	0.6	1.0	0.9	1.2	1.3	1.5	1.4	+
Phosphoric Acid Production	1.6	1.4	1.0	1.1	1.2	1.1	1.2	+
Glass Production	1.5	1.9	1.0	1.5	1.3	1.2	1.2	+
Carbon Dioxide Consumption	1.5	1.4	1.8	1.2	0.8	0.8	0.9	+
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5	+
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2	+
Agriculture	**492.5**	**565.0**	**588.8**	**590.8**	**605.5**	**611.6**	**586.8**	**8.8%**
N_2O from Agricultural Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7	4.0%
Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5	2.5%
Manure Management	51.0	72.8	76.7	78.0	78.7	81.0	78.7	1.2%
CO_2 from Fossil Fuel Combustion	31.0	46.8	46.5	47.5	49.2	50.7	49.7	0.7%
CH_4 and N_2O from Forest Fires	4.2	13.8	9.7	7.9	24.2	26.0	9.7	0.1%
Rice Cultivation	9.2	8.9	9.4	11.1	8.5	9.3	8.3	0.1%
Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9	0.1%
Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0	0.1%
CO_2, CH_4 and N_2O from Managed Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8	+
Mobile Combustion	0.3	0.5	0.5	0.5	0.5	0.6	0.5	+
Field Burning of Agricultural Residues	0.4	0.3	0.4	0.4	0.4	0.4	0.4	+
N_2O from Forest Soils	0.1	0.5	0.5	0.5	0.5	0.5	0.5	+
Stationary Combustion	+	+	+	+	+	+	+	+
Commercial	**424.8**	**429.8**	**431.9**	**396.4**	**400.7**	**374.3**	**401.1**	**6.0%**
CO_2 from Fossil Fuel Combustion	217.4	223.5	223.5	220.2	221.0	197.1	220.7	3.3%
Landfills	186.2	165.5	158.1	121.8	121.3	115.3	114.6	1.7%
Substitution of Ozone Depleting Substances	+	15.7	25.2	29.3	33.4	37.1	40.8	0.6%
Wastewater Treatment	15.7	15.9	15.6	15.5	15.3	15.2	15.0	0.2%
Human Sewage	3.4	4.3	4.6	4.7	4.8	4.9	4.9	0.1%
Composting	0.7	3.5	3.6	3.5	3.5	3.7	3.7	0.1%
Stationary Combustion	1.4	1.4	1.4	1.4	1.4	1.2	1.3	+
Residential	**346.3**	**372.8**	**360.9**	**363.7**	**360.5**	**321.5**	**375.0**	**5.6%**
CO_2 from Fossil Fuel Combustion	338.3	357.8	336.4	334.7	327.2	283.1	329.6	4.9%

Substitution of Ozone Depleting Substances	0.3	7.7	17.0	21.8	25.9	31.4	37.0	0.6%
Stationary Combustion	6.3	4.9	5.3	4.8	4.9	4.5	5.9	0.1%
Settlement Soil Fertilization	1.4	2.3	2.2	2.4	2.5	2.5	2.4	+
U.S. Territories	**33.7**	**58.2**	**47.6**	**50.6**	**43.5**	**42.1**	**34.8**	**0.5%**
CO_2 from Fossil Fuel Combustion	27.9	49.9	43.5	46.2	39.8	38.6	32.0	0.5%
Non-Energy Use of Fuels	5.7	8.1	3.9	4.2	3.6	3.3	2.7	+
Stationary Combustion	0.1	0.2	0.2	0.2	0.2	0.2	0.1	+
Total Emissions	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**	**100.0%**
Sinks	**(775.8)**	**(911.9)**	**(870.9)**	**(871.6)**	**(881.0)**	**(880.4)**	**(881.7)**	**-13.2%**
CO_2 Flux from Forests[b]	(639.4)	(807.1)	(764.9)	(765.4)	(773.8)	(773.1)	(775.7)	-11.6%
Urban Trees	(60.4)	(80.5)	(85.0)	(86.1)	(87.3)	(88.4)	(89.5)	-1.3%
Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(12.5)	(13.2)	(13.2)	(12.8)	(12.6)	-0.2%
CO_2 Flux from Agricultural Soil Carbon Stocks	(50.0)	(13.0)	(8.5)	(6.9)	(6.7)	(6.1)	(4.0)	-0.1%
Net Emissions	**5,525.2**	**6,438.3**	**5,851.9**	**6,027.2**	**5,895.6**	**5,664.7**	**5,791.2**	**86.8%**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Includes all emissions of CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, and NF_3. Parentheses indicate negative values or sequestration. Totals may not sum due to independent rounding.

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

[a] Percent of total emissions for year 2013.

[b] Includes the effects of net additions to stocks of carbon stored in harvested wood products.

Emissions with Electricity Distributed to Economic Sectors

It can also be useful to view greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). The generation, transmission, and distribution of electricity, which is the largest economic sector in the United States, accounted for 31 percent of total U.S. greenhouse gas emissions in 2013. Emissions increased by 11 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for generation. Electricity generation-related emissions increased from 2012 to 2013 by 0.8 percent, primarily due to increased CO_2 emissions from fossil fuel combustion. Electricity sales to the residential and commercial end-use sectors in 2013 increased approximately 1.2 percent and 0.9 percent, respectively. The trend in the residential and commercial sectors can largely be attributed to colder more energy-intensive winter conditions compared to 2012. Electricity sales to the industrial sector in 2013 decreased by approximately 3.1 percent. Overall, in 2013, the amount of electricity generated (in kWh) decreased by 0.1 percent from the previous year. Despite the decrease in generation, CO_2 emissions from the electric power sector increased by 0.8 percent as the consumption of CO_2 intensive coal and petroleum for electricity generation increased by 4.2 percent and 18.8 percent, respectively, in 2013 and the consumption of natural gas for electricity generation, decreased by 10.2 percent. Table 2-11 provides a detailed summary of emissions from electricity generation-related activities.

Table 2-11: Electricity Generation-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Fuel Type or Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**1,831.2**	**2,416.5**	**2,160.7**	**2,274.2**	**2,172.9**	**2,036.6**	**2,052.1**
Fossil Fuel Combustion	1,820.8	2,400.9	2,145.7	2,258.4	2,157.7	2,022.2	2,039.8
Coal	*1,547.6*	*1,983.8*	*1,740.9*	*1,827.6*	*1,722.7*	*1,511.2*	*1,575.0*
Natural Gas	*175.3*	*318.8*	*372.2*	*399.0*	*408.8*	*492.2*	*441.9*
Petroleum	*97.5*	*97.9*	*32.2*	*31.4*	*25.8*	*18.3*	*22.4*
Geothermal	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	8.0	12.5	11.3	11.0	10.5	10.4	10.1
Other Process Uses of Carbonates	2.5	3.2	3.8	4.8	4.7	4.0	2.2
CH_4	**0.3**	**0.5**	**0.4**	**0.5**	**0.4**	**0.4**	**0.4**

Stationary Combustion[a]	0.3	0.5	0.4	0.5	0.4	0.4	0.4
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**7.8**	**16.4**	**17.1**	**18.8**	**17.9**	**18.1**	**19.4**
Stationary Combustion[a]	7.4	16.0	16.8	18.5	17.6	17.8	19.1
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
SF_6	**25.4**	**10.6**	**7.3**	**7.0**	**6.8**	**5.7**	**5.1**
Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1
Total	**1,864.8**	**2,443.9**	**2,185.7**	**2,300.5**	**2,198.1**	**2,060.8**	**2,077.0**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding.

[a] Includes only stationary combustion emissions related to the generation of electricity.

+ Does not exceed 0.05 MMT CO_2 Eq.

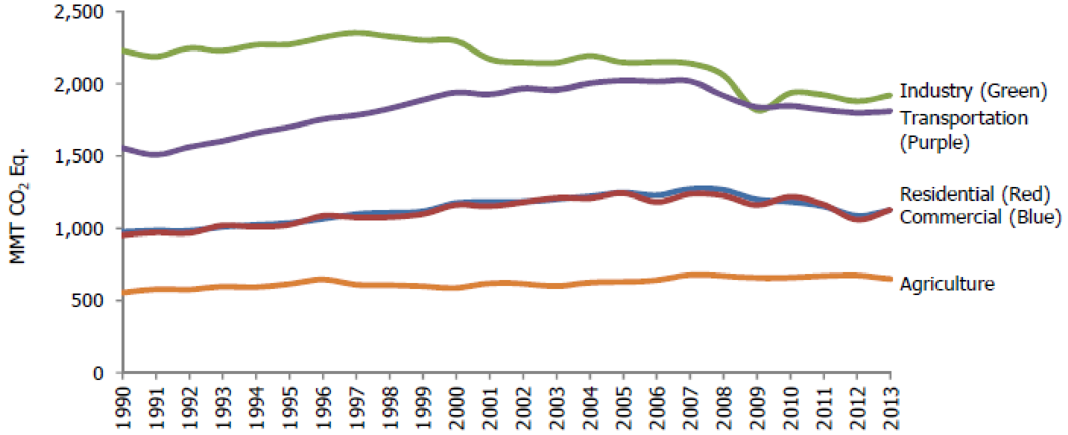
To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electricity generation sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to each economic sector's share of retail sales of electricity consumption (EIA 2015, Duffield 2006). 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 Transmission and Distribution Systems. Note that only 50 percent of the Other Process Uses of Carbonates emissions were associated with electricity generation and distributed as described; the remainder of Other Process Uses of Carbonates emissions were attributed to the industrial processes economic end-use sector.[6]

When emissions from electricity are distributed among these sectors, industrial activities account for the largest share of total U.S. greenhouse gas emissions (28.8 percent), followed closely by emissions from transportation (27.1 percent). Emissions from the residential and commercial sectors also increase substantially when emissions from electricity are included. In all sectors except agriculture, CO_2 accounts for more than 80 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 electricity generation distributed to them. Figure 2-13 shows the trend in these emissions by sector from 1990 to 2013.

Figure 2-13: Emissions with Electricity Distributed to Economic Sectors

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



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

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 2013

Sector/Gas	1990	2005	2009	2010	2011	2012	2013	Percent[a]
Industry	**2,229.7**	**2,148.5**	**1,817.7**	**1,937.7**	**1,923.9**	**1,880.9**	**1,922.6**	**28.8%**
Direct Emissions	**1,587.7**	**1,462.8**	**1,272.5**	**1,353.3**	**1,353.0**	**1,338.9**	**1,392.1**	**20.9%**
CO_2	1,158.3	1,124.5	948.9	1,026.5	1,025.7	1,029.0	1,080.6	16.2%
CH_4	317.7	273.4	277.8	272.2	261.3	252.9	255.9	3.8%
N_2O	35.3	26.6	19.9	23.6	28.9	23.8	22.5	0.3%
HFCs, PFCs, SF_6, and NF_3	76.3	38.3	25.8	31.1	37.0	33.3	33.1	0.5%
Electricity-Related	**642.0**	**685.7**	**545.2**	**584.4**	**571.0**	**542.0**	**530.5**	**8.0%**
CO_2	630.4	678.0	539.0	577.7	564.4	535.6	524.2	7.9%
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+
N_2O	2.7	4.6	4.3	4.8	4.7	4.8	5.0	0.1%
SF_6	8.7	3.0	1.8	1.8	1.8	1.5	1.3	+
Transportation	**1,554.4**	**2,022.5**	**1,839.9**	**1,848.1**	**1,819.7**	**1,799.8**	**1,810.3**	**27.1%**
Direct Emissions	**1,551.3**	**2,017.7**	**1,835.3**	**1,843.5**	**1,815.4**	**1,795.9**	**1,806.2**	**27.1%**
CO_2	1,505.6	1,898.0	1,728.9	1,741.5	1,720.5	1,709.1	1,727.2	25.9%
CH_4	5.4	2.7	2.0	1.9	1.9	1.8	1.7	+
N_2O	40.26	36.70	23.12	22.20	20.98	18.68	16.84	0.3%
HFCs[b]	+	80.4	81.4	77.9	72.0	66.3	60.5	0.9%
Electricity-Related	**3.1**	**4.8**	**4.6**	**4.6**	**4.3**	**3.9**	**4.1**	**0.1%**
CO_2	3.1	4.8	4.5	4.5	4.3	3.9	4.0	0.1%
CH_4	+	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+	+
Commercial	**975.8**	**1,247.5**	**1,199.2**	**1,183.8**	**1,152.6**	**1,088.0**	**1,126.7**	**16.9%**
Direct Emissions	**424.8**	**429.8**	**431.9**	**396.4**	**400.7**	**374.3**	**401.1**	**6.0%**
CO_2	217.4	223.5	223.5	220.2	221.0	197.1	220.7	3.3%
CH_4	203.3	184.3	176.6	140.2	139.4	133.3	132.7	2.0%
N_2O	4.1	6.3	6.6	6.7	6.8	6.8	7.0	0.1%
HFCs	+	15.7	25.2	29.3	33.4	37.1	40.8	0.6%
Electricity-Related	**551.0**	**817.7**	**767.2**	**787.4**	**751.9**	**713.6**	**725.6**	**10.9%**
CO_2	541.1	808.5	758.5	778.4	743.3	705.2	716.9	10.7%
CH_4	0.1	0.2	0.2	0.2	0.1	0.1	0.1	+
N_2O	2.3	5.5	6.0	6.4	6.1	6.3	6.8	0.1%
SF_6	7.5	3.5	2.6	2.4	2.3	2.0	1.8	+
Residential	**953.6**	**1,244.4**	**1,161.8**	**1,219.5**	**1,166.0**	**1,060.6**	**1,129.1**	**16.9%**
Direct Emissions	**346.3**	**372.8**	**360.9**	**363.7**	**360.5**	**321.5**	**375.0**	5.6%
CO_2	338.3	357.8	336.4	334.7	327.2	283.1	329.6	4.9%
CH_4	5.2	4.1	4.4	4.0	4.0	3.7	5.0	0.1%
N_2O	2.4	3.2	3.2	3.2	3.3	3.3	3.4	0.1%
HFCs	0.3	7.7	17.0	21.8	25.9	31.4	37.0	0.6%
Electricity-Related	**607.3**	**871.6**	**800.9**	**855.8**	**805.5**	**739.1**	**754.2**	**11.3%**
CO_2	596.4	861.9	791.7	846.0	796.3	730.4	745.1	11.2%
CH_4	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.5	5.8	6.3	7.0	6.6	6.5	7.1	0.1%
SF_6	8.3	3.8	2.7	2.6	2.5	2.0	1.9	+
Agriculture	**553.9**	**629.1**	**656.6**	**659.2**	**670.9**	**673.7**	**649.4**	**9.7%**
Direct Emissions	**492.5**	**565.0**	**588.8**	**590.8**	**605.5**	**611.6**	**586.8**	**8.8%**
CO_2	39.2	55.7	54.8	57.1	58.1	61.5	60.4	0.9%
CH_4	213.4	242.9	248.2	248.4	253.7	255.5	240.6	3.6%
N_2O	239.9	266.4	285.9	285.4	293.6	294.6	285.8	4.3%
Electricity-Related	**61.3**	**64.1**	**67.8**	**68.4**	**65.4**	**62.1**	**62.6**	**0.9%**
CO_2	60.2	63.4	67.0	67.6	64.7	61.4	61.9	0.9%
CH_4	+	+	+	+	+	+	+	+
N_2O	0.3	0.4	0.5	0.6	0.5	0.5	0.6	+
SF_6	0.8	0.3	0.2	0.2	0.2	0.2	0.2	+

U.S. Territories	**33.7**	**58.2**	**47.6**	**50.6**	**43.5**	**42.1**	**34.8**	**0.5%**
Total	**6,301.1**	**7,350.2**	**6,722.7**	**6,898.8**	**6,776.6**	**6,545.1**	**6,673.0**	**100.0%**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Emissions from electricity generation are allocated based on aggregate electricity consumption in each end-use sector.

Totals may not sum due to independent rounding.

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

[a] Percent of total emissions for year 2013.

[b] Includes primarily HFC-134a.

Industry

The industrial end-use sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate. This 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 methane emissions from petroleum and natural gas systems, fugitive CH_4 emissions from coal mining, by-product CO_2 emissions from cement manufacture, and HFC, PFC, SF_6, and NF_3 byproduct emissions from semiconductor manufacture, to name a few. Since 1990, industrial sector emissions have declined. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions. In addition, 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) also have a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 27 percent of U.S. greenhouse gas emissions in 2013. The largest sources of transportation greenhouse gases in 2013 were passenger cars (42.2 percent), freight trucks (22.5 percent), light duty trucks, which include sport utility vehicles, pickup trucks, and minivans (17.9 percent), commercial aircraft (6.4 percent), rail (2.6 percent), pipelines (2.6 percent), and ships and boats (2.2 percent). These figures include direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion used in transportation 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.

In terms of the overall trend, from 1990 to 2013, total transportation emissions rose by 16.5 percent due, in large part, to increased demand for travel as fleetwide 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 2013). The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 35 percent from 1990 to 2013, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. 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 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, the rate of VMT growth slowed considerably (and declined rapidly in 2008) while average new vehicle fuel economy began to increase. Average new vehicle fuel economy has improved almost every year since 2005, and the truck share has decreased to about 37 percent of new vehicles in MY 2013 (EPA 2014). Between 2012 and 2013, VMT increased by only 0.6 percent. Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals.

From 2008 to 2009, CO_2 emissions from the transportation end-use sector declined 4.2 percent. The decrease in emissions could largely be attributed to decreased economic activity in 2009 and an associated decline in the demand for transportation. Modes such as medium- and heavy-duty trucks were significantly impacted by the decline in freight transport. From 2009 to 2013, CO_2 emissions from the transportation end-use sector stabilized even as economic activity rebounded slightly.

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 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 15 percent from 1990 to 2013. This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 60.5 MMT CO_2 Eq. in 2013, led to an increase in overall emissions from transportation activities of 16 percent.

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

Gas/Vehicle	1990	2005	2009	2010	2011	2012	2013
Passenger Cars	**656.7**	**711.2**	**792.9**	**783.6**	**774.3**	**768.0**	**763.3**
CO_2	629.3	660.1	748.0	742.0	736.9	735.6	735.5
CH_4	3.2	1.4	1.2	1.2	1.2	1.1	1.1
N_2O	24.1	18.0	13.8	12.9	12.3	10.7	9.4
HFCs	+	31.7	29.9	27.5	23.9	20.6	17.3
Light-Duty Trucks	**335.6**	**553.3**	**351.6**	**349.0**	**332.1**	**326.2**	**323.4**
CO_2	321.1	504.3	310.2	308.9	295.0	292.0	292.4
CH_4	1.7	0.9	0.4	0.4	0.4	0.4	0.3
N_2O	12.8	14.8	5.8	5.5	5.1	4.4	3.9
HFCs	+	33.3	35.2	34.2	31.7	29.3	26.7
Medium- and Heavy-Duty Trucks	**231.1**	**409.8**	**389.6**	**403.0**	**401.3**	**401.4**	**407.7**
CO_2	230.1	395.9	375.1	388.4	386.8	386.8	393.2
CH_4	0.3	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.7	1.1	1.2	1.2	1.1	1.1	1.1
HFCs	+	12.7	13.2	13.2	13.3	13.3	13.3
Buses	**8.4**	**12.1**	**16.2**	**15.9**	**16.9**	**18.0**	**18.3**
CO_2	8.4	11.8	15.6	15.4	16.4	17.4	17.7
CH_4	+	+	+	+	+	+	+
N_2O	+	+	0.1	0.1	0.1	0.1	0.1
HFCs	+	0.3	0.4	0.4	0.4	0.4	0.4
Motorcycles	**1.8**	**1.7**	**4.2**	**3.7**	**3.6**	**4.2**	**4.0**
CO_2	1.7	1.6	4.1	3.6	3.6	4.1	3.9
CH_4	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+
Commercial Aircraft[a]	**110.9**	**133.9**	**120.6**	**114.3**	**115.6**	**114.3**	**115.4**
CO_2	109.9	132.7	119.5	113.3	114.6	113.3	114.3
CH_4	+	+	+	+	+	+	+
N_2O	1.0	1.2	1.1	1.0	1.1	1.0	1.1
Other Aircraft[b]	**78.3**	**59.6**	**36.8**	**40.4**	**34.2**	**32.1**	**34.7**
CO_2	77.5	59.1	36.4	40.1	33.9	31.8	34.4
CH_4	0.1	0.1	+	+	+	+	+
N_2O	0.7	0.5	0.3	0.4	0.3	0.3	0.3
Ships and Boats[c]	**44.9**	**45.2**	**38.9**	**45.0**	**46.7**	**40.4**	**39.6**
CO_2	44.3	44.5	38.4	44.2	45.8	39.6	38.9
CH_4	+	+	+	+	+	+	+
N_2O	0.6	0.6	0.5	0.8	0.8	0.7	0.7
HFCs	+	+	+	+	+	+	+
Rail	**39.0**	**53.3**	**43.7**	**46.5**	**48.1**	**46.8**	**47.5**
CO_2	38.5	50.3	40.7	43.4	45.0	43.7	44.4
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	+	2.5	2.6	2.6	2.6	2.6	2.6
Other Emissions from Electricity Generation[d]	0.1	0.1	+	+	+	+	+
Pipelines[e]	**36.0**	**32.2**	**36.7**	**37.1**	**37.8**	**40.3**	**47.7**
CO_2	36.0	32.2	36.7	37.1	37.8	40.3	47.7
Lubricants	**11.8**	**10.2**	**8.5**	**9.5**	**9.0**	**8.3**	**8.8**

CO_2	11.8	10.2	8.5	9.5	9.0	8.3	8.8
Total Transportation	**1,554.4**	**2,022.5**	**1,839.9**	**1,848.1**	**1,819.7**	**1,799.8**	**1,810.3**
International Bunker Fuels[f]	*104.5*	*114.2*	*107.5*	*118.1*	*112.8*	*106.8*	*100.7*

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

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

+ 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 electricity generation are a result of waste incineration (as the majority of municipal solid waste is combusted in "trash-to-steam" electricity generation plants), electrical transmission and distribution, and a portion of Other Process Uses of Carbonates (from pollution control equipment installed in electricity generation 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 U.S. Inventory.

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

Commercial

The commercial sector is heavily reliant on electricity for meeting energy needs, with electricity consumption for 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 residential and commercial sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. Landfills and wastewater treatment are included in this sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions decreasing slightly.

Residential

The residential sector is heavily reliant on electricity for meeting energy needs, with electricity consumption for 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 sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. In the long-term, this sector is also affected by population growth, regional migration trends, and changes in housing and building attributes (e.g., size and insulation).

Agriculture

The agriculture sector includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2013, 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 like tractors. The agriculture sector is less reliant on electricity than the other sectors.

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 IPCC sectors common for UNFCCC reporting. Discussing greenhouse gas emissions relevant to U.S.-specific sectors improves communication of the report's findings.

In the Electricity Generation economic sector, CO_2 emissions from the combustion of fossil fuels included in the EIA electric utility fuel consuming sector are apportioned to this economic sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA electric utility sector. Additional sources include CO_2, CH_4, and N_2O from waste incineration, as the majority of municipal solid waste is combusted in "trash-to-steam" electricity generation plants. The Electricity Generation economic sector also includes SF_6 from Electrical Transmission and Distribution, and a portion of CO_2 from Other Process Uses of Carbonates (from pollution control equipment installed in electricity generation plants).

In the Transportation economic sector, the CO_2 emissions from the combustion of fossil fuels included in the EIA transportation fuel consuming sector are apportioned to this economic sector (additional analyses and refinement of the EIA data is further explained in the Energy chapter of this report). Additional emissions are apportioned from the CH_4 and N_2O from Mobile Combustion, based on the EIA transportation sector. Substitutes of Ozone Depleting Substances are apportioned based on their specific end-uses within the source category, with emissions from transportation refrigeration/air-conditioning systems to this economic sector. Finally, CO_2 emissions from Non-Energy Uses of Fossil Fuels identified as lubricants for transportation vehicles are included in the Transportation economic sector.

For the Industry economic sector, the CO_2 emissions from the combustion of fossil fuels included in the EIA industrial fuel consuming sector, minus the agricultural use of fuel explained below, are apportioned to this economic sector. Stationary and mobile combustion emissions of CH_4 and N_2O are also based on the EIA industrial sector, minus emissions apportioned to the Agriculture economic sector described below. Substitutes of Ozone Depleting Substances are apportioned based on their specific end-uses within the source category, with most emissions falling within the Industry economic sector (minus emissions from the other economic sectors). Additionally, all process-related emissions from sources with methods considered within the IPCC Industrial Process guidance have been apportioned to this 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 such activities 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) are 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.

As agriculture equipment is included in EIA's industrial fuel consuming sector surveys, additional data is used to extract the fuel used by agricultural equipment, to allow for accurate reporting in the Agriculture economic sector from all sources of emissions, such as motorized farming equipment. Energy consumption estimates are obtained from Department of Agriculture survey data, in combination with separate EIA fuel sales reports. This supplementary data is used to apportion CO_2 emissions from fossil fuel combustion, and CH_4 and N_2O emissions from stationary and mobile combustion (all data is removed from the Industrial economic sector, to avoid double-counting). The other emission sources included in this economic sector are intuitive for the agriculture sectors, such as N_2O emissions from Agricultural Soils, CH_4 from Enteric Fermentation (i.e., exhalation from the digestive tracts of domesticated animals), CH_4 and N_2O from Manure Management, CH_4 from Rice Cultivation, CO_2 emissions from Liming of Agricultural Soils and Urea Application, and CH_4 and N_2O from Forest Fires. N_2O emissions from the Application of Fertilizers to tree plantations (termed "forest land" by the IPCC) are also included in the Agriculture economic sector.

The Residential economic sector includes the CO_2 emissions from the combustion of fossil fuels reported for the EIA residential sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel consuming sector. Substitutes of Ozone Depleting Substances are apportioned based on their specific end-uses within the source category, with emissions from residential air-conditioning systems to this economic sector. 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 the CO_2 emissions from the combustion of fossil fuels reported in the EIA commercial fuel consuming sector data. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA commercial sector. Substitutes of Ozone Depleting Substances are apportioned based on their specific end-uses within the source category, with emissions from commercial refrigeration/air-conditioning systems to this economic sector. Public works sources including direct CH_4 from Landfills and CH_4 and N_2O from Wastewater Treatment and Composting are included in this economic sector.

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

Total emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy consumption, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of electricity consumption, because the electric power industry—utilities and non-utilities combined—was the largest source of U.S. greenhouse gas emissions in 2013; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) 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. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.3 percent since 1990. Since 1990, this rate is slightly slower than that for total energy and for fossil fuel consumption, and much slower than that for electricity consumption, overall gross domestic product and national population (see Table 2-14).

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

Chapter/IPCC Sector	1990	2005	2009	2010	2011	2012	2013	Growth[a]
Greenhouse Gas Emissions [b]	100	117	107	109	108	104	106	0.3%
Energy Consumption [c]	100	118	112	116	115	112	115	0.6%
Fossil Fuel Consumption [c]	100	119	108	112	110	107	110	0.4%
Electricity Consumption [c]	100	134	131	137	137	135	135	1.3%
GDP [d]	100	159	161	165	168	172	175	2.5%
Population [e]	100	118	123	124	125	125	126	1.0%

[a] Average annual growth rate

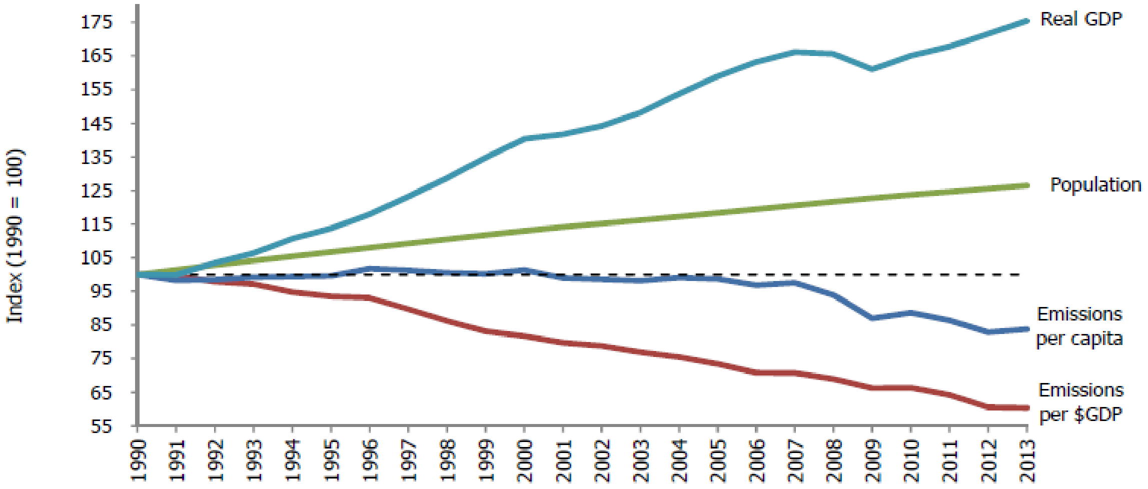
[b] GWP-weighted values

[c] Energy-content-weighted values (EIA 2015)

[d] Gross Domestic Product in chained 2009 dollars (BEA 2014)

[e] U.S. Census Bureau (2014)

Figure 2-14: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2014), U.S. Census Bureau (2014), and emission estimates in this report.

2.2 Indirect Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the UNFCCC[7] request that information be provided on indirect greenhouse gases, which include CO, NO_x, NMVOCs, and SO_2. These gases do not have a direct global warming effect, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Carbon monoxide is produced when carbon-containing fuels are combusted incompletely. Nitrogen oxides (i.e., NO and NO_2) are created by lightning, fires, fossil fuel combustion, and in the stratosphere from N_2O. Non-CH_4 volatile organic compounds—which include hundreds of organic compounds that participate in atmospheric chemical reactions (i.e., propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, 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. Sulfur-containing compounds emitted into the atmosphere tend to exert a negative radiative forcing (i.e., cooling) and therefore are discussed separately.

One important indirect climate change effect of NMVOCs and NO_x is their role as precursors for tropospheric ozone formation. They can also alter the atmospheric lifetimes of other greenhouse gases. Another example of indirect greenhouse gas formation into greenhouse gases is CO's interaction with the hydroxyl radical—the major atmospheric sink for CH_4 emissions—to form CO_2. Therefore, increased atmospheric concentrations of CO limit the number of hydroxyl molecules (OH) available to destroy CH_4.

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[7] See < http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

Since 1970, the United States has published estimates of emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2015),[8] which are regulated under the Clean Air Act. Table 2-15 shows that fuel combustion accounts for the majority of emissions of these indirect greenhouse gases. 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.

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

Gas/Activity	1990	2005	2009	2010	2011	2012	2013
NO_x	**21,771**	**17,394**	**13,450**	**12,607**	**12,630**	**11,912**	**11,167**
Mobile Fossil Fuel Combustion	10,862	10,295	7,797	7,290	7,294	6,788	6,283
Stationary Fossil Fuel Combustion	10,023	5,858	4,452	4,092	3,807	3,567	3,579
Oil and Gas Activities	139	321	468	545	622	622	622
Industrial Processes and Product Use	592	572	493	472	452	452	452
Forest Fires	64	212	149	121	373	400	149
Waste Combustion	82	128	81	77	73	73	73
Agricultural Burning	8	6	8	8	8	8	8
Waste	+	2	1	1	1	1	1
CO	**132,337**	**74,283**	**51,716**	**50,996**	**58,868**	**58,022**	**47,265**
Mobile Fossil Fuel Combustion	119,360	58,615	39,256	39,475	38,305	36,491	34,676
Forest Fires	2,300	7,550	5,313	4,323	13,291	14,262	5,310
Stationary Fossil Fuel Combustion	5,000	4,648	4,036	4,103	4,170	4,170	4,170
Industrial Processes and Product Use	4,129	1,557	1,331	1,280	1,229	1,229	1,229
Waste Combustion	978	1,403	1,164	1,084	1,003	1,003	1,003
Oil and Gas Activities	302	318	363	487	610	610	610
Agricultural Burning	268	184	247	241	255	253	262
Waste	1	7	5	5	5	5	5
NMVOCs	**20,930**	**13,154**	**11,586**	**11,641**	**11,726**	**11,416**	**11,107**
Mobile Fossil Fuel Combustion	10,932	5,724	4,650	4,591	4,562	4,252	3,942
Industrial Processes and Product Use	7,638	5,849	4,337	4,133	3,929	3,929	3,929
Oil and Gas Activities	554	510	1,894	2,205	2,517	2,517	2,517
Stationary Fossil Fuel Combustion	912	716	553	576	599	599	599
Waste Combustion	222	241	103	92	81	81	81
Waste	673	114	49	44	38	38	38
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**13,196**	**8,246**	**7,015**	**5,877**	**4,711**	**4,625**
Stationary Fossil Fuel Combustion	18,407	11,541	7,228	6,120	5,008	3,859	3,790
Industrial Processes and Product Use	1,307	831	654	618	605	605	605
Oil and Gas Activities	390	180	126	117	108	108	108
Mobile Fossil Fuel Combustion	793	619	220	144	142	125	108
Waste Combustion	38	25	17	16	15	15	15
Waste	+	1	1	+	+	+	+
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA

Source: (EPA 2015) except for estimates from Field Burning of Agricultural Residues.

NA (Not Available)

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

Box 2-3: Sources and Effects of Sulfur Dioxide

Sulfur dioxide (SO_2) emitted into the atmosphere through natural and anthropogenic processes affects the earth's radiative budget through its photochemical transformation into sulfate aerosols that can (1) scatter radiation from the sun back to space, thereby reducing the radiation reaching the earth's surface; (2) affect cloud formation; and (3)

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[8] NO_x and CO emission estimates from Field Burning of Agricultural Residues were estimated separately, and therefore not taken from EPA (2015).

affect atmospheric chemical composition (e.g., by providing surfaces for heterogeneous chemical reactions). The indirect effect of sulfur-derived aerosols on radiative forcing can be considered in two parts. The first indirect effect is the aerosols' tendency to decrease water droplet size and increase water droplet concentration in the atmosphere. The second indirect effect is the tendency of the reduction in cloud droplet size to affect precipitation by increasing cloud lifetime and thickness. Although still highly uncertain, the radiative forcing estimates from both the first and the second indirect effect are believed to be negative, as is the combined radiative forcing of the two (IPCC 2001). However, because SO_2 is short-lived and unevenly distributed in the atmosphere, its radiative forcing impacts are highly uncertain.

Sulfur dioxide is also a major contributor to the formation of regional haze, which can cause significant increases in acute and chronic respiratory diseases. Once SO_2 is emitted, it is chemically transformed in the atmosphere and returns to the earth as the primary source of acid rain. Because of these harmful effects, the United States has regulated SO_2 emissions in the Clean Air Act.

Electricity generation is the largest anthropogenic source of SO_2 emissions in the United States, accounting for 64.4 percent in 2013. Coal combustion contributes nearly all of those emissions (approximately 92 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result of electric power generators switching from high-sulfur to low-sulfur coal and installing flue gas desulfurization equipment.

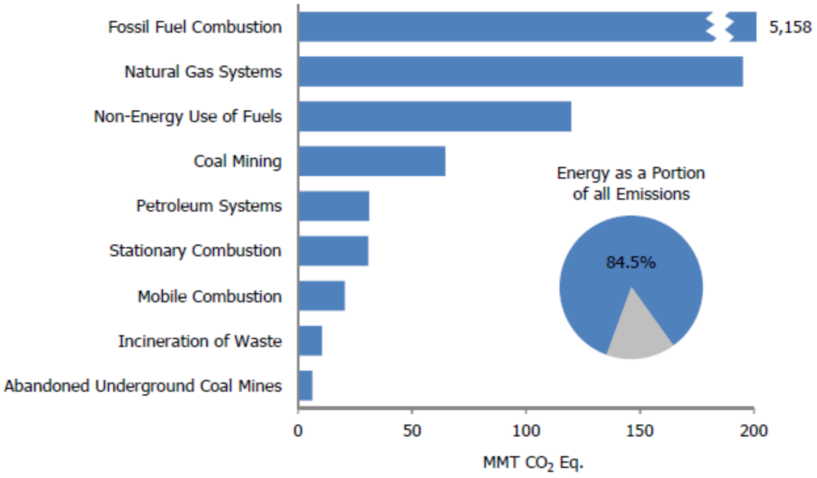
3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 84.5 percent of total greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis in 2013.[1] This included 97, 41, and 12 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 79.9 percent of national 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 national emissions (4.6 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1). Globally, approximately 32,310 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2012, of which the United States accounted for approximately 16 percent.[2] Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered separately, and in more detail than other energy-related emissions (see Figure 3-2). 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 third largest source.

Figure 3-1: 2013 Energy Chapter Greenhouse Gas Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



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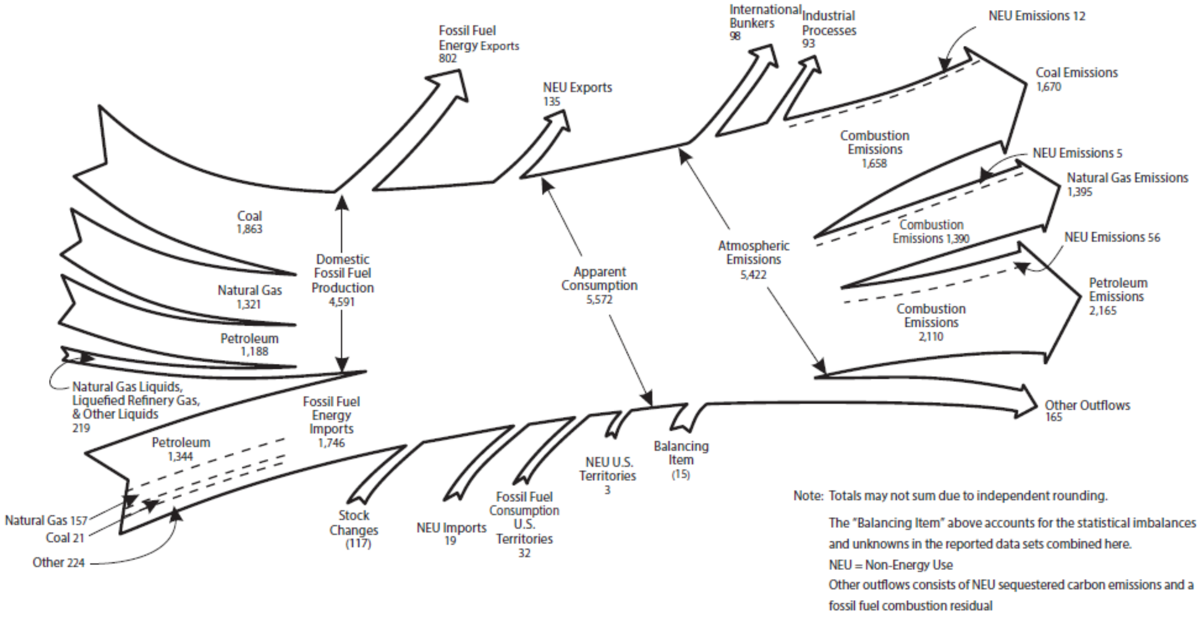
[1] Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

[2] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Statistics 2013* <http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm> EIA (2013).

Figure 3-2: 2013 U.S. Fossil Carbon Flows (MMT CO_2 Eq.)

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Note: Totals may not sum due to independent rounding.

The "Balancing Item" above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

NEU = Non-Energy Use

Other outflows consists of NEU sequestered carbon emissions and a fossil fuel combustion residual

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 from natural gas systems, petroleum systems, and coal mining. Table 3-1 summarizes emissions from the Energy sector in units of million metric tons of CO_2 equivalents (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 5,636.6 MMT CO_2 Eq. in 2013,[3] an increase of 6.5 percent since 1990.

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

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**4,908.4**	**5,933.9**	**5,351.2**	**5,529.2**	**5,390.3**	**5,181.1**	**5,331.5**
Fossil Fuel Combustion	4,740.7	5,747.7	5,197.1	5,367.1	5,231.3	5,026.0	5,157.7
Electricity Generation	1,820.8	2,400.9	2,145.7	2,258.4	2,157.7	2,022.2	2,039.8
Transportation	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4
Industrial	842.5	827.8	727.7	775.7	774.1	784.2	817.3
Residential	338.3	357.8	336.4	334.7	327.2	283.1	329.6
Commercial	217.4	223.5	223.5	220.2	221.0	197.1	220.7
U.S. Territories	27.9	49.9	43.5	46.2	39.8	38.6	32.0
Non-Energy Use of Fuels	117.7	138.9	106.0	114.6	108.4	104.9	119.8
Natural Gas Systems	37.6	30.0	32.2	32.3	35.6	34.8	37.8
Incineration of Waste	8.0	12.5	11.3	11.0	10.5	10.4	10.1
Petroleum Systems	4.4	4.9	4.7	4.2	4.5	5.1	6.0
Biomass – Wood[a]	*215.2*	*206.9*	*188.2*	*192.5*	*195.2*	*194.9*	*208.6*
International Bunker Fuels[a]	*103.5*	*113.1*	*106.4*	*117.0*	*111.7*	*105.8*	*99.8*
Biomass – Ethanol[a]	*4.2*	*22.9*	*62.3*	*72.6*	*72.9*	*72.8*	*74.7*
CH_4	**328.5**	**280.9**	**285.5**	**279.2**	**268.2**	**259.2**	**263.5**
Natural Gas Systems	179.1	176.3	168.0	159.6	159.3	154.4	157.4
Coal Mining	96.5	64.1	79.9	82.3	71.2	66.5	64.6

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[3] Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

Petroleum Systems	31.5	23.5	21.5	21.3	22.0	23.3	25.2
Stationary Combustion	8.5	7.4	7.4	7.1	7.1	6.6	8.0
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.6	6.4	6.2	6.2
Mobile Combustion	5.6	3.0	2.3	2.3	2.3	2.2	2.1
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[a]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**53.6**	**58.7**	**45.3**	**46.2**	**44.1**	**41.9**	**41.6**
Stationary Combustion	11.9	20.2	20.4	22.2	21.3	21.4	22.9
Mobile Combustion	41.2	38.1	24.6	23.7	22.5	20.2	18.4
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
International Bunker Fuels[a]	*0.9*	*1.0*	*0.9*	*1.0*	*1.0*	*0.9*	*0.9*
Total	**5,290.5**	**6,273.6**	**5,682.1**	**5,854.6**	**5,702.6**	**5,482.2**	**5,636.6**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] These values are presented for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations, and are not included in the specific energy sector contribution to the totals, and are already accounted for elsewhere.

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	2009	2010	2011	2012	2013
CO_2	**4,908,390**	**5,933,912**	**5,351,228**	**5,529,210**	**5,390,268**	**5,181,104**	**5,331,493**
Fossil Fuel Combustion	4,740,670	5,747,683	5,197,058	5,367,144	5,231,341	5,026,000	5,157,697
Non-Energy Use of Fuels	117,658	138,877	106,018	114,554	108,359	104,917	119,850
Natural Gas Systems	37,645	29,995	32,201	32,334	35,551	34,764	37,808
Incineration of Waste	7,972	12,454	11,295	11,026	10,550	10,363	10,137
Petroleum Systems	4,445	4,904	4,656	4,153	4,467	5,060	6,001
Biomass –Wood[a]	*215,186*	*206,901*	*188,220*	*192,462*	*195,182*	*194,903*	*208,594*
International Bunker Fuels[a]	*103,463*	*113,139*	*106,410*	*116,992*	*111,660*	*105,805*	*99,763*
Biomass – Ethanol[a]	*4,227*	*22,943*	*62,272*	*72,647*	*72,881*	*72,827*	*74,743*
CH_4	**13,139**	**11,237**	**11,419**	**11,168**	**10,729**	**10,366**	**10,541**
Natural Gas Systems	7,165	7,053	6,722	6,382	6,371	6,176	6,295
Coal Mining	3,860	2,565	3,194	3,293	2,849	2,658	2,584
Petroleum Systems	1,261	939	860	854	878	931	1,009
Stationary Combustion	339	296	295	283	283	264	318
Abandoned Underground Coal Mines	288	264	254	263	257	249	249
Mobile Combustion	225	121	93	92	91	88	86
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[a]	*7*	*5*	*5*	*6*	*5*	*4*	*3*
N_2O	**180**	**197**	**152**	**155**	**148**	**141**	**140**
Stationary Combustion	40	68	69	74	71	72	77
Mobile Combustion	138	128	82	80	76	68	62
Incineration of Waste	2	1	1	1	1	1	1
International Bunker Fuels[a]	*3*	*3*	*3*	*3*	*3*	*3*	*3*

+ Does not exceed 0.5 kt

[a] These values are presented for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations, and are not included in the specific energy sector contribution to the totals, and are already accounted for elsewhere.

Note: Totals may not sum due to independent rounding.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks 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). Additionally, the calculated emissions and sinks in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. Emissions and sinks provided in this Inventory do not preclude alternative examinations, but rather, this Inventory presents emissions and sinks in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

Box 3-2: Energy Data from the Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases (GHG) from large GHG emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP). 40 CFR Part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons. Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. 40 CFR part 98 requires reporting by 41 industrial categories. Data reporting by affected facilities included the reporting of emissions from fuel combustion at that affected facility. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.

The GHGRP dataset and the data presented in this inventory report are complementary and, as indicated in the respective planned improvements sections for source categories in this chapter, EPA is analyzing how to use facility-level GHGRP data to improve the national estimates presented in this Inventory (see, also, Box 3-4). Most methodologies used in EPA's GHGRP are consistent with IPCC, though 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. 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 UNFCCC reporting guidelines. In line with the 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. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the GHGRP website.

EPA presents the data collected by its GHGRP through a data publication tool that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.

3.1 Fossil Fuel Combustion (IPCC Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the 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. Following that is a discussion of emissions of all three gases from fossil fuel combustion presented by sectoral breakdowns. Methodologies for estimating CO_2 from fossil fuel combustion also 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	2009	2010	2011	2012	2013
CO_2	4,740.7	5,747.7	5,197.1	5,367.1	5,231.3	5,026.0	5,157.7
CH_4	14.1	10.4	9.7	9.4	9.3	8.8	10.1
N_2O	53.1	58.4	45.0	45.9	43.8	41.6	41.3
Total	**4,807.9**	**5,816.5**	**5,251.8**	**5,422.5**	**5,284.5**	**5,076.4**	**5,209.1**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

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

Gas	1990	2005	2009	2010	2011	2012	2013
CO_2	4,740,670	5,747,683	5,197,058	5,367,144	5,231,341	5,026,000	5,157,697
CH_4	565	416	389	375	374	352	404
N_2O	178	196	151	154	147	140	139

Note: Totals may not sum due to independent rounding

CO_2 from Fossil Fuel Combustion

CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. CO_2 emissions from fossil fuel combustion are presented in Table 3-5. In 2013, CO_2 emissions from fossil fuel combustion increased by 2.6 percent relative to the previous year. The increase in CO_2 emissions from fossil fuel combustion was a result of multiple factors, including: (1) an increase in the price of natural gas leading to increased coal-fired generation in the electric power sector; (2) much colder winter conditions resulting in an increased demand for heating fuel in the residential and commercial sectors; (3) an increase in industrial production across multiple sectors resulting in increases in industrial sector emissions;[4] and (4) an increase in transportation emissions resulting from an increase in vehicle miles traveled (VMT) and fuel use across on-road transportation modes. In 2013, CO_2 emissions from fossil fuel combustion were 5,157.7 MMT CO_2 Eq., or 8.8 percent above emissions in 1990 (see Table 3-5).[5]

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

Fuel/Sector	1990	2005	2009	2010	2011	2012	2013
Coal	**1,718.4**	**2,112.3**	**1,834.2**	**1,927.7**	**1,813.9**	**1,592.8**	**1,658.1**
Residential	3.0	0.8	0.0	0.0	0.0	0.0	0.0
Commercial	12.0	9.3	6.9	6.6	5.8	4.1	3.9
Industrial	155.3	115.3	83.0	90.1	82.0	74.1	75.8
Transportation	NE	NE	NE	NE	NE	NE	NE
Electricity Generation	1,547.6	1,983.8	1,740.9	1,827.6	1,722.7	1,511.2	1,575.0
U.S. Territories	0.6	3.0	3.4	3.4	3.4	3.4	3.4
Natural Gas	**1,000.3**	**1,166.7**	**1,216.9**	**1,272.1**	**1,291.5**	**1,352.6**	**1,389.5**
Residential	238.0	262.2	258.8	258.6	254.7	224.8	267.1
Commercial	142.1	162.9	168.9	167.7	170.5	156.9	178.2
Industrial	408.9	388.5	377.6	407.2	417.3	434.8	450.8
Transportation	36.0	33.1	37.9	38.1	38.9	41.3	48.8
Electricity Generation	175.3	318.8	372.2	399.0	408.8	492.2	441.9
U.S. Territories	NO	1.3	1.5	1.5	1.4	2.6	2.6
Petroleum	**2,021.5**	**2,468.4**	**2,145.5**	**2,167.0**	**2,125.5**	**2,080.2**	**2,109.6**

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

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

Residential	97.4	94.9	77.6	76.2	72.6	58.3	62.5
Commercial	63.3	51.3	47.7	45.9	44.7	36.1	38.6
Industrial	278.3	324.0	267.0	278.4	274.8	275.4	290.6
Transportation	1,457.7	1,854.7	1,682.4	1,693.9	1,672.7	1,659.5	1,669.6
Electricity Generation	97.5	97.9	32.2	31.4	25.8	18.3	22.4
U.S. Territories	27.2	45.6	38.6	41.3	34.9	32.6	26.0
Geothermal[a]	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**4,740.7**	**5,747.7**	**5,197.1**	**5,367.1**	**5,231.3**	**5,026.0**	**5,157.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

NE (Not estimated)

NO (Not occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes.

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.

Longer-term changes in energy consumption patterns, however, tend to be more a function of aggregate societal trends that affect the scale of consumption (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, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

CO_2 emissions also depend on the source of energy and its carbon (C) intensity. The amount of C in fuels varies significantly by fuel type. For example, coal contains the highest amount of C per unit of useful energy. Petroleum has roughly 75 percent of the C per unit of energy as coal, and natural gas has only about 55 percent.[6] 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 2013 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO_2 Eq. and Percent)

Sector	Fuel Type	2009 to 2010		2010 to 2011		2011 to 2012		2012 to 2013		Total 2013
Electricity Generation	Coal	86.7	5.0%	-104.9	-5.7%	-211.5	-12.3%	63.8	4.2%	1,575.0
Electricity Generation	Natural Gas	26.8	7.2%	9.8	2.5%	83.5	20.4%	-50.3	-10.2%	441.9
Electricity Generation	Petroleum	-0.8	-2.4%	-5.6	-17.8%	-7.5	-29.0%	4.1	22.2%	22.4
Transportation[a]	Petroleum	11.4	0.7%	-21.2	-1.3%	-13.2	-0.8%	10.2	0.6%	1,669.6
Residential	Natural Gas	-0.3	-0.1%	-3.9	-1.5%	-29.8	-11.7%	42.3	18.8%	267.1
Commercial	Natural Gas	-1.2	-0.7%	2.7	1.6%	-13.6	-8.0%	21.4	13.6%	178.2
Industrial	Coal	7.0	8.5%	-8.1	-9.0%	-7.9	-9.7%	1.8	2.4%	75.8
Industrial	Natural Gas	29.6	7.8%	10.1	2.5%	17.5	4.2%	16.0	3.7%	450.8
All Sectors[b]	**All Fuels[b]**	**170.1**	**3.3%**	**-135.8**	**-2.5%**	**-205.3**	**-3.9%**	**131.7**	**2.6%**	**5,157.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Excludes emissions from International Bunker Fuels.

[b] Includes fuels and sectors not shown in table.

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[6] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States.

In the United States, 82 percent of the energy consumed in 2013 was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 3-3 and Figure 3-4). The remaining portion was supplied by nuclear electric power (9 percent) and by a variety of renewable energy sources (10 percent), primarily hydroelectric power, wind energy and biofuels (EIA 2015).[7] Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 36 percent of total U.S. energy consumption in 2013. Natural gas and coal followed in order of energy demand importance, accounting for approximately 28 percent and 19 percent of total U.S. energy consumption, respectively. Petroleum was consumed primarily in the transportation end-use sector and the vast majority of coal was used in electricity generation. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-5) (EIA 2015).

Figure 3-3: 2013 U.S. Energy Consumption by Energy Source (percent)

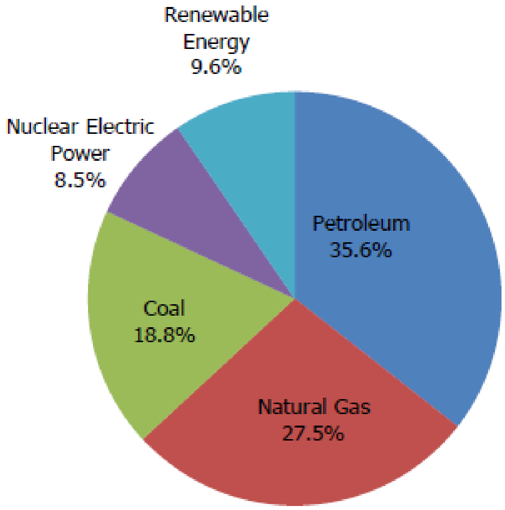
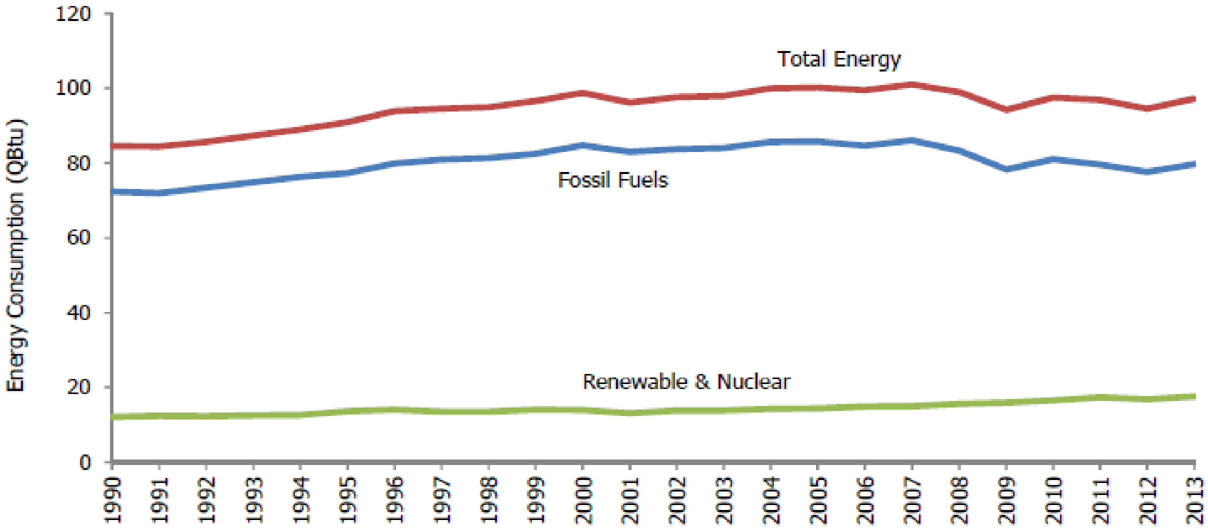


Figure 3-4: U.S. Energy Consumption (Quadrillion Btu)



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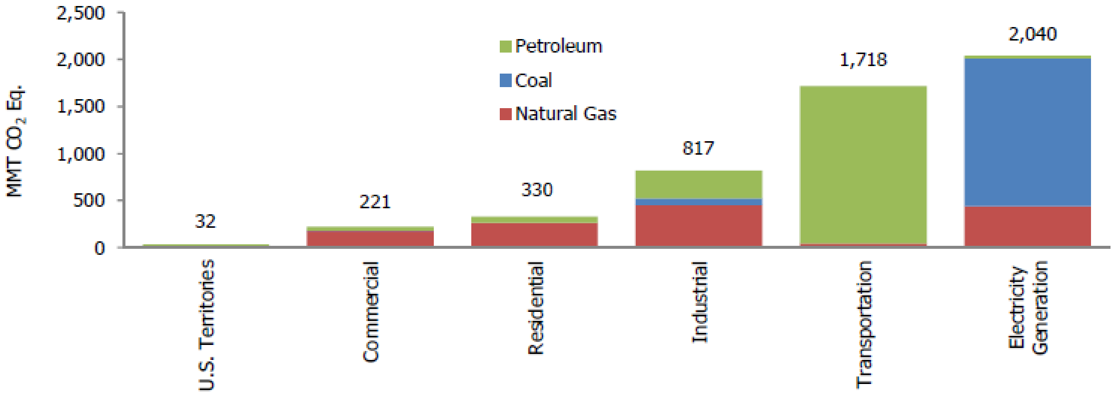
[7] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biofuels, solar energy, and wind energy.

Figure 3-5: 2013 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO_2 Eq.)



Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the C stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, CO, and NMVOCs.[8] 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, it is assumed all of the C in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

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

In 2013, weather conditions, and a very cold first quarter of the year in particular, caused a significant increase in energy demand for heating fuels and is reflected in the increased residential emissions during the early part of the year (EIA 2015). The United States in 2013 also experienced a cooler winter overall compared to 2012, as heating degree days increased (18.5 percent). Cooling degree days decreased by 12.8 percent and despite this decrease in cooling degree days, electricity demand to cool homes still increased slightly. While colder winter conditions compared to 2012 resulted in a significant increase in the amount of energy required for heating, heating degree days in the United States were 1.2 percent below normal (see Figure 3-6). Summer conditions were slightly cooler in 2013 compared to 2012, and summer temperatures were warmer than normal, with cooling degree days 7.1 percent above normal (see Figure 3-7) (EIA 2015).[9]

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

[9] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F, while cooling degree days are deviations of the mean daily temperature above 65° F. 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 1971 through 2000. The variation in these normals during this time period was ±10 percent and ±14 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1950–2013)

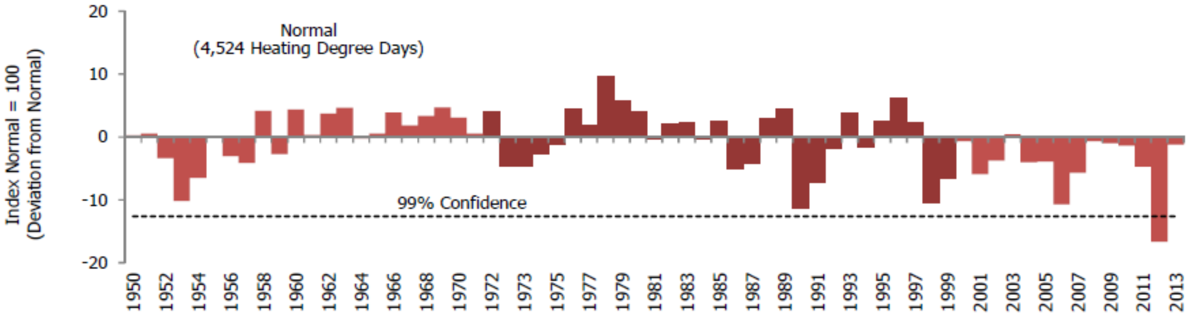
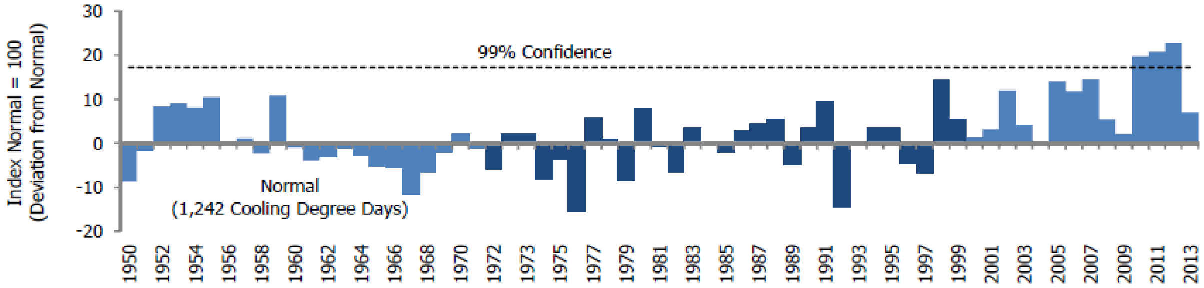


Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950–2013)



Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors)[10] of existing plants in 2013 remained high at 91 percent. Electricity output by hydroelectric power plants decreased in 2013 by approximately 3 percent. In recent years, the wind power sector has been showing strong growth, such that, on the margin, it is becoming a relatively important electricity source. Electricity generated by nuclear plants in 2013 provided nearly 3 times as much of the energy generated in the United States from hydroelectric plants (EIA 2015). Nuclear, hydroelectric, and wind power capacity factors since 1990 are shown in Figure 3-8.

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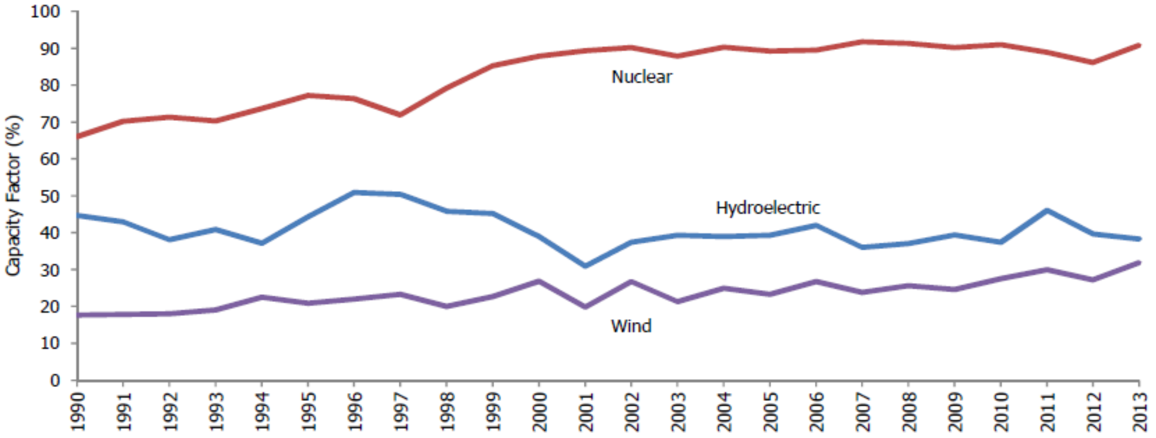
[10] The capacity factor equals generation divided by net summer capacity. Summer capacity is defined as "The maximum output that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)." Data for both the generation and net summer capacity are from EIA (2015).

Figure 3-8: Nuclear, Hydroelectric, and Wind Power Plant Capacity Factors in the United States (1990–2013)



Fossil Fuel Combustion Emissions by Sector

In addition to the CO_2 emitted from fossil fuel combustion, CH_4 and N_2O are emitted from stationary and mobile combustion as well. Table 3-7 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector.

Table 3-7: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Electricity Generation	**1,828.5**	**2,417.4**	**2,162.9**	**2,277.4**	**2,175.8**	**2,040.4**	**2,059.3**
CO_2	1,820.8	2,400.9	2,145.7	2,258.4	2,157.7	2,022.2	2,039.8
CH_4	0.3	0.5	0.4	0.5	0.4	0.4	0.4
N_2O	7.4	16.0	16.8	18.5	17.6	17.8	19.1
Transportation	**1,540.6**	**1,928.9**	**1,747.2**	**1,758.0**	**1,736.3**	**1,723.2**	**1,739.0**
CO_2	1,493.8	1,887.8	1,720.3	1,732.0	1,711.5	1,700.8	1,718.4
CH_4	5.6	3.0	2.3	2.3	2.3	2.2	2.1
N_2O	41.2	38.1	24.6	23.7	22.5	20.2	18.4
Industrial	**847.4**	**832.4**	**731.4**	**779.6**	**778.0**	**788.2**	**821.2**
CO_2	842.5	827.8	727.7	775.7	774.1	784.2	817.3
CH_4	1.8	1.7	1.4	1.5	1.5	1.5	1.5
N_2O	3.1	2.9	2.3	2.5	2.4	2.4	2.4
Residential	**344.6**	**362.8**	**341.7**	**339.6**	**332.1**	**287.6**	**335.5**
CO_2	338.3	357.8	336.4	334.7	327.2	283.1	329.6
CH_4	5.2	4.1	4.4	4.0	4.0	3.7	5.0
N_2O	1.0	0.9	0.9	0.8	0.8	0.7	1.0
Commercial	**218.8**	**224.9**	**224.9**	**221.6**	**222.4**	**198.3**	**222.1**
CO_2	217.4	223.5	223.5	220.2	221.0	197.1	220.7
CH_4	1.0	1.1	1.1	1.1	1.0	0.9	1.0
N_2O	0.4	0.3	0.3	0.3	0.3	0.3	0.3
U.S. Territories[a]	**28.0**	**50.1**	**43.7**	**46.4**	**39.9**	**38.8**	**32.1**
Total	**4,807.9**	**5,816.5**	**5,251.8**	**5,422.5**	**5,284.5**	**5,076.4**	**5,209.1**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

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

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

Other than CO_2, gases emitted from stationary combustion include the greenhouse gases CH_4 and N_2O and the indirect greenhouse gases NO_x, CO, and NMVOCs.[11] Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics, size and vintage, along with combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. N_2O 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 produces greenhouse gases other than CO_2, including CH_4, N_2O, and indirect greenhouse gases 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. N_2O 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 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 electricity generation to the sectors in which it is used. Four end-use sectors were defined: industrial, transportation, residential, and commercial. In the table below, electricity generation emissions have been distributed to each end-use sector based upon the sector's share of national electricity consumption, with the exception of CH_4 and N_2O from transportation.[12] Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data. This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity consumption in that sector. The results of this alternative method are presented in Table 3-8.

Table 3-8: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Transportation	**1,543.7**	**1,933.7**	**1,751.7**	**1,762.5**	**1,740.6**	**1,727.1**	**1,743.0**
CO_2	1,496.8	1,892.5	1,724.8	1,736.5	1,715.8	1,704.6	1,722.4
CH_4	5.6	3.0	2.3	2.3	2.3	2.2	2.1
N_2O	41.2	38.1	24.6	23.8	22.5	20.3	18.5
Industrial	**1,537.0**	**1,574.1**	**1,338.0**	**1,425.8**	**1,407.9**	**1,386.3**	**1,409.3**
CO_2	1,529.2	1,564.4	1,329.5	1,416.5	1,398.8	1,377.0	1,399.8
CH_4	2.0	1.9	1.5	1.6	1.6	1.6	1.6
N_2O	5.9	7.8	7.0	7.7	7.6	7.7	7.9
Residential	**940.2**	**1,224.9**	**1,134.3**	**1,186.7**	**1,129.4**	**1,019.4**	**1,083.3**
CO_2	931.4	1,214.1	1,122.6	1,174.8	1,117.9	1,008.4	1,070.2
CH_4	5.4	4.2	4.6	4.2	4.2	3.9	5.1
N_2O	3.4	6.6	7.1	7.7	7.3	7.1	7.9
Commercial	**759.1**	**1,033.7**	**984.2**	**1,001.0**	**966.6**	**904.9**	**941.5**

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[11] Sulfur dioxide (SO_2) emissions from stationary combustion are addressed in Annex 6.3.

[12] Separate calculations were performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions are discussed in the mobile combustion section.

CO_2	755.4	1,026.7	976.7	993.2	959.1	897.4	933.3
CH_4	1.1	1.2	1.2	1.2	1.2	1.1	1.2
N_2O	2.5	5.7	6.2	6.6	6.3	6.4	7.0
U.S. Territories[a]	**28.0**	**50.1**	**43.7**	**46.4**	**39.9**	**38.8**	**32.1**
Total	**4,807.9**	**5,816.5**	**5,251.8**	**5,422.5**	**5,284.5**	**5,076.4**	**5,209.1**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

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

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

Stationary Combustion

The direct combustion of fuels by stationary sources in the electricity generation, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-9 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 Methodology section of CO_2 from Fossil Fuel Combustion). Other than CO_2, gases emitted from stationary combustion include the greenhouse gases CH_4 and N_2O. Table 3-10 and Table 3-11 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources.[13] Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics, combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. N_2O 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. The CH_4 and N_2O emission estimation methodology was revised in 2010 to utilize the facility-specific technology and fuel use data reported to EPA's Acid Rain Program (see Methodology section for CH_4 and N_2O from stationary combustion). Please refer to Table 3-7 for the corresponding presentation of all direct emission sources of fuel combustion.

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

Sector/Fuel Type	1990	2005	2009	2010	2011	2012	2013
Electricity Generation	**1,820.8**	**2,400.9**	**2,145.7**	**2,258.4**	**2,157.7**	**2,022.2**	**2,039.8**
Coal	1,547.6	1,983.8	1,740.9	1,827.6	1,722.7	1,511.2	1,575.0
Natural Gas	175.3	318.8	372.2	399.0	408.8	492.2	441.9
Fuel Oil	97.5	97.9	32.2	31.4	25.8	18.3	22.4
Geothermal	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Industrial	**842.5**	**827.8**	**727.7**	**775.7**	**774.1**	**784.2**	**817.3**
Coal	155.3	115.3	83.0	90.1	82.0	74.1	75.8
Natural Gas	408.9	388.5	377.6	407.2	417.3	434.8	450.8
Fuel Oil	278.3	324.0	267.0	278.4	274.8	275.4	290.6
Commercial	**217.4**	**223.5**	**223.5**	**220.2**	**221.0**	**197.1**	**220.7**
Coal	12.0	9.3	6.9	6.6	5.8	4.1	3.9
Natural Gas	142.1	162.9	168.9	167.7	170.5	156.9	178.2
Fuel Oil	63.3	51.3	47.7	45.9	44.7	36.1	38.6
Residential	**338.3**	**357.8**	**336.4**	**334.7**	**327.2**	**283.1**	**329.6**
Coal	3.0	0.8	+	+	+	+	+
Natural Gas	238.0	262.2	258.8	258.6	254.7	224.8	267.1
Fuel Oil	97.4	94.9	77.6	76.2	72.6	58.3	62.5
U.S. Territories	**27.9**	**49.9**	**43.5**	**46.2**	**39.8**	**38.6**	**32.0**
Coal	0.6	3.0	3.4	3.4	3.4	3.4	3.4

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[13] Since emission estimates for U.S. territories cannot be disaggregated by gas in Table 3-10 and Table 3-11, the values for CH_4 and N_2O exclude U.S. territory emissions.

Natural Gas	NO	1.3	1.5	1.5	1.4	2.6	2.6
Fuel Oil	27.2	45.6	38.6	41.3	34.9	32.6	26.0
Total	**3,246.9**	**3,859.9**	**3,476.7**	**3,635.2**	**3,519.8**	**3,325.2**	**3,439.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO: Not occurring

Table 3-10: CH_4 Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2009	2010	2011	2012	2013
Electric Power	**0.3**	**0.5**	**0.4**	**0.5**	**0.4**	**0.4**	**0.4**
Coal	0.3	0.3	0.3	0.3	0.3	0.2	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Wood	+	+	+	+	+	+	+
Industrial	**1.8**	**1.7**	**1.4**	**1.5**	**1.5**	**1.5**	**1.5**
Coal	0.4	0.3	0.2	0.2	0.2	0.2	0.2
Fuel Oil	0.2	0.2	0.1	0.2	0.1	0.1	0.2
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.0	1.0	0.8	0.9	0.9	1.0	0.9
Commercial/Institutional	**1.0**	**1.1**	**1.1**	**1.1**	**1.0**	**0.9**	**1.0**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Natural gas	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Wood	0.5	0.5	0.5	0.5	0.5	0.4	0.5
Residential	**5.2**	**4.1**	**4.4**	**4.0**	**4.0**	**3.7**	**5.0**
Coal	0.2	0.1	+	+	+	+	+
Fuel Oil	0.3	0.3	0.3	0.3	0.3	0.2	0.2
Natural Gas	0.5	0.6	0.6	0.6	0.6	0.5	0.6
Wood	4.1	3.1	3.6	3.1	3.2	3.0	4.1
U.S. Territories	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**+**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	0.1	0.1	0.1	0.1	+
Natural Gas	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+
Total	**8.5**	**7.4**	**7.4**	**7.1**	**7.1**	**6.6**	**8.0**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-11: N_2O Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2009	2010	2011	2012	2013
Electricity Generation	**7.4**	**16.0**	**16.8**	**18.5**	**17.6**	**17.8**	**19.1**
Coal	6.3	11.6	11.2	12.5	11.5	10.2	12.1
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	1.0	4.3	5.6	5.9	6.1	7.5	7.0
Wood	+	+	+	+	+	+	+
Industrial	**3.1**	**2.9**	**2.3**	**2.5**	**2.4**	**2.4**	**2.4**
Coal	0.7	0.5	0.4	0.4	0.4	0.4	0.4
Fuel Oil	0.5	0.5	0.4	0.4	0.4	0.3	0.4
Natural Gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.6	1.6	1.3	1.4	1.5	1.5	1.4
Commercial/Institutional	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	0.1	+	+	+	+	+	+
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	**1.0**		**0.9**		**0.9**	**0.8**	**0.8**	**0.7**	**1.0**
Coal	+		+		+	+	+	+	+
Fuel Oil	0.2		0.2		0.2	0.2	0.2	0.2	0.2
Natural Gas	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Wood	0.7		0.5		0.6	0.5	0.5	0.5	0.7
U.S. Territories	**0.1**		**0.1**		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+		+		+	+	+	+	+
Fuel Oil	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Natural Gas	+		+		+	+	+	+	+
Wood	+		+		+	+	+	+	+
Total	**11.9**		**20.2**		**20.4**	**22.2**	**21.3**	**21.4**	**22.9**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

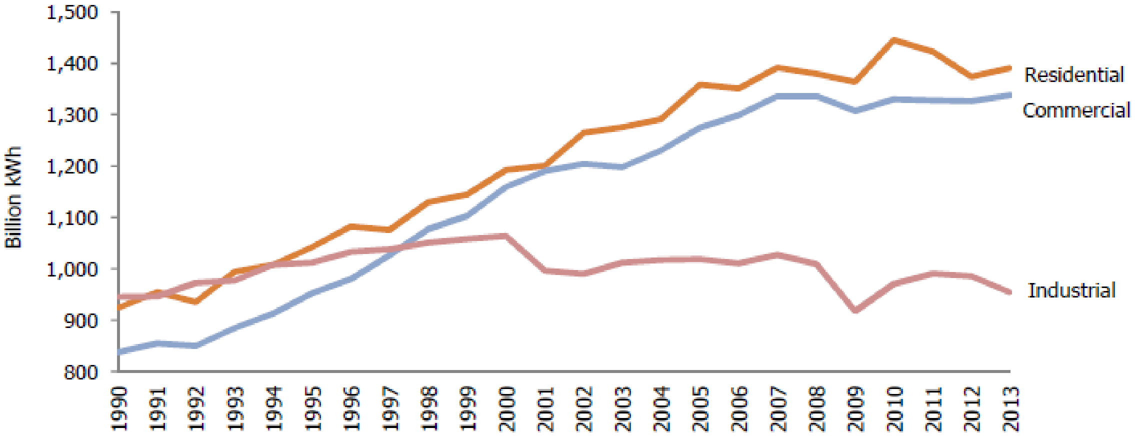
+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Electricity Generation

The process of generating electricity is the single largest source of CO_2 emissions in the United States, representing 37 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 emissions from electricity generation, representing less than 0.1 percent and 0.9 percent, respectively. Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 39.5 percent in 2013. Methane and N_2O from electricity generation represented 4.2 and 46.3 percent of total methane and N_2O emissions from fossil fuel combustion in 2013, respectively. Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-9). Electricity generators, including those using low-CO_2 emitting technologies, relied on coal for approximately 39 percent of their total energy requirements in 2013. Recently an increase in the carbon intensity of fuels consumed to generate electricity has occurred due to an increase in coal consumption, and decreased natural gas consumption and other generation sources. Total U.S. electricity generators used natural gas for approximately 27 percent of their total energy requirements in 2013 (EIA 2014a).

Figure 3-9: Electricity Generation Retail Sales by End-Use Sector



The electric power industry includes all power producers, consisting of both regulated utilities and nonutilities (e.g. independent power producers, qualifying cogenerators, and other small power producers). 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 electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity, while the other sectors consist of those producers that indicate their primary business is something other than the production of electricity.[14]

The industrial, residential, and commercial end-use sectors, as presented in Table 3-8, were reliant on electricity for meeting energy needs. The residential and commercial end-use sectors were especially reliant on electricity consumption for lighting, heating, air conditioning, and operating appliances. Electricity sales to the residential and commercial end-use sectors in 2013 increased approximately 1.2 percent and 0.9 percent, respectively. The trend in the residential and commercial sectors can largely be attributed to colder, more energy-intensive winter conditions compared to 2012. Electricity sales to the industrial sector in 2013 decreased approximately 3.1 percent. Overall, in 2013, the amount of electricity generated (in kWh) decreased approximately 0.1 percent relative to the previous year, while CO_2 emissions from the electric power sector increased by 0.9 percent. The increase in CO_2 emissions, despite the decrease in sales and electricity generation was a result of an increase in the consumption of coal and petroleum for electricity generation by 4.2 percent and 18.8 percent, respectively, in 2013, and a decrease in the consumption of natural gas for electricity generation by 10.2 percent.

Industrial Sector

Industrial sector CO_2, CH_4, and N_2O, emissions accounted for 16, 15, and 6 percent of CO_2, CH_4, and N_2O, emissions from fossil fuel combustion, respectively. CO_2, CH_4, and N_2O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial sector, per the underlying energy consumption data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy consumption is manufacturing, of which six industries—Petroleum Refineries, Chemicals, Paper, Primary Metals, Food, and Nonmetallic Mineral Products—represent the vast majority of the energy use (EIA 2015 and EIA 2009b).

In theory, emissions from the industrial sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions.[15] In addition, 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) also have a significant effect on industrial emissions.

From 2012 to 2013, total industrial production and manufacturing output increased by 2.9 percent (FRB 2014). Over this period, output increased across production indices for Food, Petroleum Refineries, Chemicals, Primary Metals, and Nonmetallic Mineral Products, and decreased slightly for Paper (see Figure 3-10). Through EPA's Greenhouse Gas Reporting Program (GHGRP), industrial trends can be discerned from the overall EIA industrial fuel consumption data used for these calculations. For example, from 2012 to 2013 the underlying EIA data showed increased consumption of natural gas and petroleum fuels in the industrial sector. EPA's GHGRP data highlights that petroleum refineries, chemical manufacturing, and non-metallic mineral products were contributors to these trends.[16]

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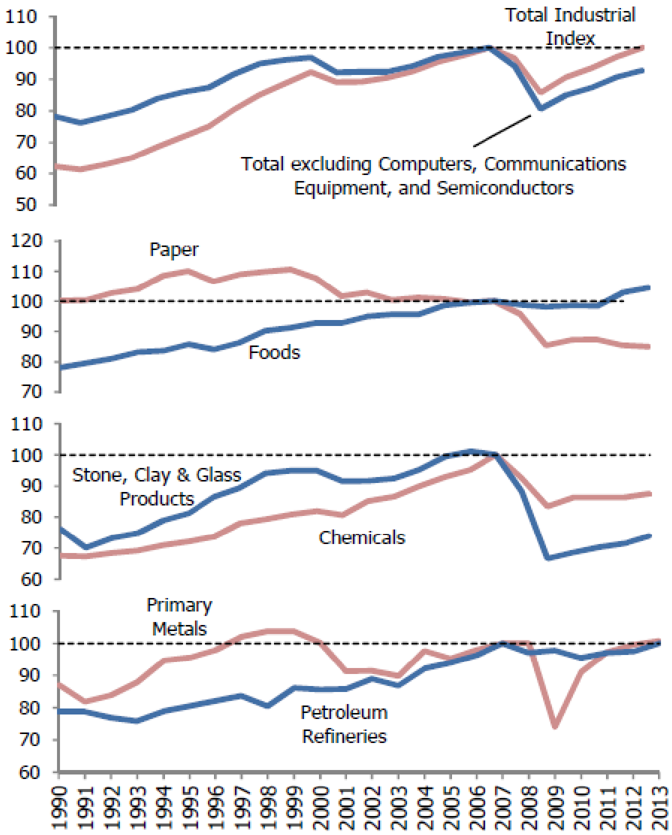
[14] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Nonutilities produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to customers).

[15] 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.

[16] Further details on industrial sector combustion emissions are provided by EPA's GHGRP (<http://ghgdata.epa.gov/ghgp/main.do>).

Figure 3-10: Industrial Production Indices (Index 2007=100)



Despite the growth in industrial output (61 percent) and the overall U.S. economy (75 percent) from 1990 to 2013, CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 3.0 percent over the same time series. A number of factors are believed to have caused this disparity between growth in industrial output and decrease in industrial emissions, including: (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. In 2013, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,409.3 MMT CO_2 Eq., or approximately 1.7 percent above 2012 emissions.

Residential and Commercial Sectors

Residential and commercial sector CO_2 emissions accounted for 6 and 4 percent of CO_2 emissions from fossil fuel combustion, CH_4 emissions accounted for 49 and 10 percent of CH_4 emissions from fossil fuel combustion, and N_2O emissions accounted for 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors were largely due to 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 both of these end-use sectors. In 2013, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,083.3 MMT CO_2 Eq. and 941.5 MMT CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors increased by 6.3 and 4.0 percent from 2012 to 2013, respectively.

Emissions from the residential and commercial sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. In the long-term, both sectors are also affected by population growth, regional migration trends, and changes in housing and building attributes (e.g., size and insulation).

In 2013, combustion emissions from natural gas consumption represent 81 percent of the direct fossil fuel CO_2 emissions from both the residential and commercial sectors. Natural gas combustion CO_2 emissions from the residential and commercial sectors in 2013 increased by 18.8 percent and 13.6 percent from 2012 levels, 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 U.S. Pacific Islands. As described in the Methodology section for 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, though the emissions will include some 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 3-8. For direct emissions from transportation (i.e., not including emissions associated with the sector's electricity consumption), please see Table 3-7.

Transportation End-Use Sector

The transportation end-use sector accounted for 1,743.0 MMT CO_2 Eq. in 2013, which represented 33 percent of CO_2 emissions, 21 percent of CH_4 emissions, and 45 percent of N_2O emissions from fossil fuel combustion, respectively.[17] Fuel purchased in the United States for international aircraft and marine travel accounted for an additional 100.7 MMT CO_2 Eq. in 2013; these emissions are recorded as international bunkers and are not included in U.S. totals according to UNFCCC reporting protocols.

From 1990 to 2013, transportation emissions from fossil fuel combustion rose by 13 percent due, in large part, to increased demand for travel with limited gains in fuel efficiency for much of this time period. The number of vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) increased 35 percent from 1990 to 2013, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period.

From 2012 to 2013, CO_2 emissions from the transportation end-use sector increased by 1.0 percent.[18] The increase in emissions can largely be attributed to small increases in VMT and fuel use across on-road transportation modes, as well as increases in other non-road sectors such as pipelines. Commercial aircraft emissions increased slightly between 2012 and 2013, but have decreased 18 percent since 2007. Decreases in jet fuel emissions (excluding bunkers) since 2007 are 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.

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 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 15 percent from 1990 to 2013. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

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[17] Note that these totals include 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.

[18] Note that this value does not include lubricants.

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 15 percent (225.6 MMT CO_2) between 1990 and 2013, an annualized increase of 0.6 percent. Among domestic transportation sources, light duty vehicles (including passenger cars and light-duty trucks) represented 60 percent of CO_2 emissions from fossil fuel combustion, medium- and heavy-duty trucks 23 percent, commercial aircraft 7 percent, and other sources 11 percent. See Table 3-12 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. CO_2 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.[19] Ethanol consumption from the transportation sector has increased from 0.7 billion gallons in 1990 to 12.6 billion gallons in 2013, while biodiesel consumption has increased from 0.01 billion gallons in 2001 to 1.4 billion gallons in 2013. For further information, see the section on biofuel consumption at the end of this chapter and Table A-93 in Annex 3.2.

CO_2 emissions from passenger cars and light-duty trucks totaled 1,028.0 MMT CO_2 in 2013, an increase of 8 percent (77.6 MMT CO_2) from 1990 due, in large part, to increased demand for travel as fleetwide 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 2013). CO_2 emissions from passenger cars and light-duty trucks peaked at 1,181.2 MMT CO_2 in 2004, and since then have declined about 13 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (Figure 3-11) reflected 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 (Figure 3-12). Starting in 2005, the rate of VMT growth slowed considerably (and declined rapidly in 2008) while average new vehicle fuel economy began to increase. Average new vehicle fuel economy has improved almost every year since 2005, and the truck share has decreased to about 37 percent of new vehicles in model year 2013 (EPA 2014d).

Medium- and heavy-duty truck CO_2 emissions increased by 71 percent from 1990 to 2013. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 92 percent between 1990 and 2013.[20] Carbon dioxide from the domestic operation of commercial aircraft increased by 4 percent (4.4 MMT CO_2) from 1990 to 2013. Across all categories of aviation, excluding international bunkers, CO_2 emissions decreased by 21 percent (38.7 MMT CO_2) between 1990 and 2013.[21] This includes a 69 percent (24.0 MMT CO_2) decrease in CO_2 emissions from domestic military operations.

Transportation sources also produce CH_4 and N_2O; these emissions are included in Table 3-13 and Table 3-14 in the "Mobile Combustion" Section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

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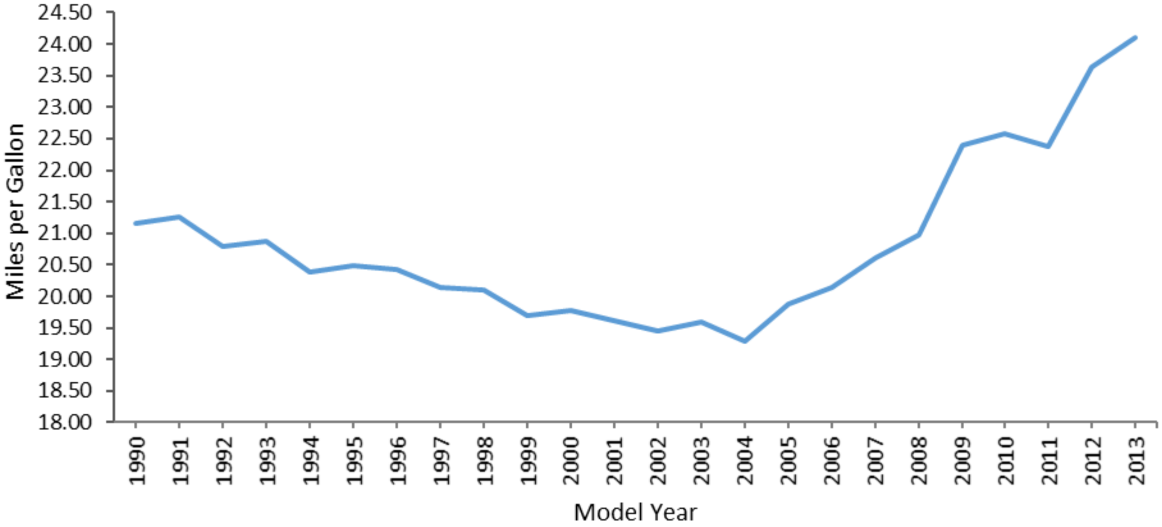
[19] Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA's "Renewable Fuels: Regulations & Standards;" See <http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm>.

[20] While FHWA data shows consistent growth in medium- and heavy-duty truck VMT over the 1990 to 2013 time period, part of the growth reflects a method change for estimating VMT starting in 2007. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class, thus leading to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2013 time period. During the time period prior to the method change (1990-2006), VMT for medium- and heavy-duty trucks increased by 51 percent.

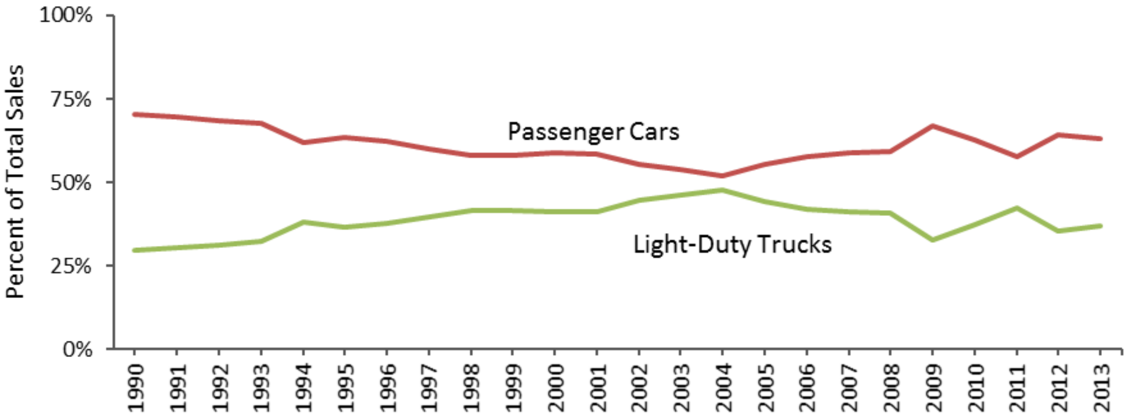
[21] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-11: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2013 (miles/gallon)



Source: EPA (2014)

Figure 3-12: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2013 (percent)



Source: EPA (2014)

Table 3-12: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO_2 Eq.)

Fuel/Vehicle Type	1990	2005	2009[a]	2010	2011	2012	2013
Gasoline[c]	**983.5**	**1,183.9**	**1,101.7**	**1,092.7**	**1,069.0**	**1,064.9**	**1,065.8**
Passenger Cars	621.4	655.9	744.3	738.2	732.8	731.5	731.5
Light-Duty Trucks	309.1	477.2	296.9	295.0	280.4	277.4	277.7
Medium- and Heavy-Duty Trucks[b]	38.7	34.8	42.6	42.3	38.9	38.7	39.5
Buses	0.3	0.4	0.7	0.7	0.7	0.8	0.8
Motorcycles	1.7	1.6	4.1	3.6	3.6	4.1	3.9
Recreational Boats	12.2	14.1	13.0	12.7	12.6	12.5	12.4
Distillate Fuel Oil (Diesel)[c]	**262.9**	**458.1**	**409.0**	**425.5**	**433.7**	**431.3**	**437.6**
Passenger Cars	7.9	4.2	3.6	3.8	4.1	4.1	4.1
Light-Duty Trucks	11.5	25.8	12.1	12.6	13.1	13.0	13.0

Medium- and Heavy-Duty Trucks[b]	190.5	360.6	332.0	345.6	347.3	347.5	353.0
Buses	8.0	10.6	13.7	13.6	14.6	15.5	15.8
Rail	35.5	45.6	36.2	39.0	40.8	39.8	40.4
Recreational Boats	2.0	3.1	3.5	3.5	3.6	3.7	3.7
Ships and Other Boats	7.5	8.1	7.9	7.5	10.3	7.6	7.7
International Bunker Fuels[d]	*11.7*	*9.4*	*8.2*	*9.5*	*7.9*	*6.8*	*5.6*
Jet Fuel	**184.2**	**189.3**	**154.1**	**151.5**	**146.6**	**143.4**	**147.1**
Commercial Aircraft[e]	109.9	132.7	119.5	113.3	114.6	113.3	114.3
Military Aircraft	35.0	19.4	15.4	13.6	11.6	12.1	11.0
General Aviation Aircraft	39.4	37.3	19.2	24.6	20.4	18.0	21.8
International Bunker Fuels[d]	*38.0*	*60.1*	*52.8*	*61.0*	*64.8*	*64.5*	*65.7*
International Bunker Fuels from Commercial Aviation	*30.0*	*55.6*	*49.2*	*57.4*	*61.7*	*61.4*	*62.8*
Aviation Gasoline	**3.1**	**2.4**	**1.8**	**1.9**	**1.9**	**1.7**	**1.5**
General Aviation Aircraft	3.1	2.4	1.8	1.9	1.9	1.7	1.5
Residual Fuel Oil	**22.6**	**19.3**	**13.9**	**20.4**	**19.4**	**15.8**	**15.0**
Ships and Other Boats	22.6	19.3	13.9	20.4	19.4	15.8	15.0
International Bunker Fuels[d]	*53.7*	*43.6*	*45.4*	*46.5*	*38.9*	*34.5*	*28.5*
Natural Gas	**36.0**	**33.1**	**37.9**	**38.1**	**38.9**	**41.3**	**48.8**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Buses	+	0.8	1.2	1.1	1.1	1.0	1.0
Pipeline[f]	36.0	32.2	36.7	37.1	37.8	40.3	47.7
LPG	**1.4**	**1.7**	**1.7**	**1.8**	**2.1**	**2.3**	**2.5**
Light-Duty Trucks	0.6	1.3	1.2	1.3	1.5	1.6	1.8
Medium- and Heavy-Duty Trucks[b]	0.8	0.4	0.5	0.6	0.6	0.7	0.7
Buses	+	+	+	+	+	+	+
Electricity	**3.0**	**4.7**	**4.5**	**4.5**	**4.3**	**3.9**	**4.0**
Rail	3.0	4.7	4.5	4.5	4.3	3.9	4.0
Ethanol[g]	***4.1***	***22.4***	***61.2***	***71.3***	***71.5***	***71.5***	***73.4***
Total	**1,496.8**	**1,892.5**	**1,724.8**	**1,736.5**	**1,715.8**	**1,704.6**	**1,722.4**
Total (Including Bunkers)[d]	**1,600.3**	**2,005.7**	**1,831.2**	**1,853.4**	**1,827.5**	**1,810.4**	**1,822.2**

Note: 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.

[a] In 2011 FHWA changed its methods for estimating vehicle miles traveled (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 for the 2010 Inventory and apply to the 2007-13 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

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

[c] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table VM-1 and MF-27.

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

[e] Commercial aircraft, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights.

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

[g] Ethanol 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 UNFCCC reporting obligations, for more information on ethanol.

Note: Totals may not sum due to independent rounding.

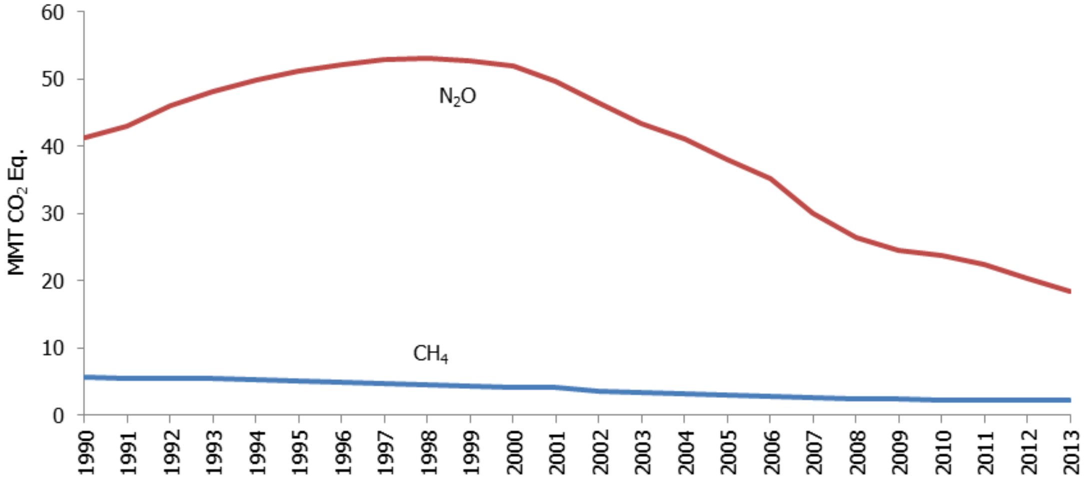
\+ Less than 0.05 MMT CO_2 Eq.

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;[22] 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.).[23] Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-13 and Table 3-14 provide mobile fossil fuel CH_4 and N_2O emission estimates in MMT CO_2 Eq.[24]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.3 percent) but was the third largest source of U.S. N_2O emissions (5.2 percent). From 1990 to 2013, mobile source CH_4 emissions declined by 62 percent, to 2.1 MMT CO_2 Eq. (86 kt CH_4), due largely to 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 55 percent, to 18.4 MMT CO_2 Eq. (62 kt N_2O). Earlier generation control technologies initially resulted in higher N_2O emissions, causing a 28 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 65 percent decrease in mobile source N_2O emissions from 1997 to 2013 (Figure 3-13). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks.

Figure 3-13: Mobile Source CH_4 and N_2O Emissions (MMT CO_2 Eq.)



Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

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[22] 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.

[23] 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 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 Commercial 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 emissions 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.

[24] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2013.

Table 3-13: CH_4 Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2009	2010	2011	2012	2013
Gasoline On-Road[b]	**5.2**	**2.4**	**1.7**	**1.7**	**1.6**	**1.5**	**1.5**
Passenger Cars	3.2	1.4	1.2	1.2	1.2	1.1	1.0
Light-Duty Trucks	1.7	0.9	0.4	0.4	0.4	0.3	0.3
Medium- and Heavy-Duty Trucks and Buses	0.3	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Road	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.6**
Ships and Boats	+	+	+	+	+	+	+
Rail[f]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[c]	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Construction/Mining Equipment[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other[e]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**5.6**	**3.0**	**2.3**	**2.3**	**2.3**	**2.2**	**2.1**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values. Totals may not sum due to independent rounding.

Note: In 2011, FHWA changed its methods for estimating vehicle miles traveled (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 for the 1990-2010 Inventory and apply to the 2007 through 2013 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

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

[b] Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1.

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

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

[e] “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.

[f] Rail emissions do not include emissions from electric powered locomotives.

+ Less than 0.05 MMT CO_2 Eq.

Table 3-14: N_2O Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2009	2010	2011	2012	2013
Gasoline On-Road[b]	**37.4**	**33.6**	**20.4**	**19.2**	**18.0**	**15.8**	**13.9**
Passenger Cars	24.1	18.0	13.8	12.9	12.3	10.7	9.3
Light-Duty Trucks	12.7	14.8	5.7	5.5	5.0	4.4	3.9
Medium- and Heavy-Duty Trucks and Buses	0.5	0.8	0.8	0.8	0.7	0.7	0.7
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**0.2**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	0.2	0.3	0.4	0.4	0.4	0.4	0.4

Alternative Fuel On-Road	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**
Non-Road	**3.5**	**4.1**	**3.7**	**4.0**	**4.0**	**3.9**	**3.9**
Ships and Boats	0.6	0.6	0.5	0.8	0.8	0.7	0.7
Rail[f]	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Aircraft	1.7	1.8	1.4	1.4	1.4	1.3	1.4
Agricultural Equipment[c]	0.2	0.3	0.3	0.4	0.4	0.4	0.4
Construction/Mining Equipment[d]	0.3	0.5	0.5	0.5	0.6	0.6	0.6
Other[e]	0.4	0.6	0.6	0.6	0.6	0.6	0.6
Total	**41.2**	**38.1**	**24.6**	**23.7**	**22.5**	**20.2**	**18.4**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values. Totals may not sum due to independent rounding.

Note: In 2011, FHWA changed its methods for estimating vehicle miles traveled (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 for the 1990-2010 Inventory and apply to the 2007 through 2013 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

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

[b] Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1.

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

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

[e] "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.

[f] Rail emissions do not include emissions from electric powered locomotives.

+ Less than 0.05 MMT CO_2 Eq.

CO_2 from Fossil Fuel Combustion

Methodology

The methodology used by the United States for estimating CO_2 emissions from fossil fuel combustion is conceptually similar to the approach recommended by the IPCC for countries that intend to develop detailed, sectoral-based emission estimates in line with a Tier 2 method in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).[25] The use of the most recently published calculation methodologies by the IPCC, as contained in the *2006 IPCC Guidelines*, is considered to improve the rigor and accuracy of this inventory and is fully in line with IPCC Good Practice Guidance. 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, etc.), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil, etc.). 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 and published supplemental tables on petroleum product detail (EIA 2015). 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 2013) and Jacobs (2010).[26]

   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

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[25] The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

[26] 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 emissions of 32.1 MMT CO_2 Eq. in 2013.

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 data sets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[27]

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).[28]

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 2013), Coffeyville (2014), U.S. Census Bureau (2011), EIA (2014c), USGS (1991 through 2011), USGS (1994 through 2011), USGS (1995, 1998, 2000 through 2002), USGS (2007), USGS (2009), USGS (2010), USGS (2011), USGS (1991 through 2010a), USGS (1991 through 2010b), USGS (2012a) and USGS (2012b).[29]

3. *Adjust for conversion of fuels and exports of CO_2.* Fossil fuel consumption estimates are adjusted downward to exclude fuels created from other fossil fuels and exports of CO_2.[30] Synthetic natural gas is created from industrial coal, and is currently included in EIA statistics for both coal and natural gas. Therefore, synthetic natural gas is subtracted from energy consumption statistics.[31] Since October 2000, the Dakota Gasification Plant has been exporting CO_2 to Canada by pipeline. Since this CO_2 is not emitted to the atmosphere in the United States, energy used to produce this CO_2 is subtracted from energy consumption statistics. To make these adjustments, additional data for ethanol were collected from EIA (2015), data for synthetic natural gas were collected from EIA (2014), and data for CO_2 exports were collected from the Eastman Gasification Services Company (2011), Dakota Gasification Company (2006), Fitzpatrick (2002), Erickson (2003), EIA (2008) and DOE (2012).

4. *Adjust Sectoral Allocation of Distillate Fuel Oil and Motor Gasoline*. EPA had 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 was 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 2013), Benson

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[27] 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.

[28] 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.

[29] 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.

[30] Energy statistics from EIA (2015) are already adjusted downward to account for ethanol added to motor gasoline, and biogas in natural gas.

[31] These adjustments are explained in greater detail in Annex 2.1.

(2002 through 2004), DOE (1993 through 2014), EIA (2007), EIA (1991 through 2014), EPA (2013b), and FHWA (1996 through 2014).[32]

5. *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 C contained in the fuel for a period of time. As the emission pathways of C used for non-energy purposes are vastly different than fuel combustion (since the C in these fuels ends up in products instead of being combusted), these emissions are estimated separately in the Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption was provided by EIA (2015).

6. *Subtract consumption of international bunker fuels.* According to the 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 for emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of C content).[33] 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 2014) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was obtained from FAA (2015); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2013) for 1990 through 2001 and 2007 through 2013, and DHS (2008) for 2003 through 2006. Consumption of these fuels was subtracted from the corresponding fuels in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail later in the International Bunker Fuels section of this chapter.

7. *Determine the total C content of fuels consumed.* Total C was estimated by multiplying the amount of fuel consumed by the amount of C in each fuel. This total C estimate defines the maximum amount of C that could potentially be released to the atmosphere if all of the C in each fuel was converted to CO_2. The C content coefficients used by the United States were obtained from EIA's Emissions of Greenhouse Gases in the United States 2008 (EIA 2009a), and an EPA analysis of C content coefficients used in the GHGRP (EPA 2010). A discussion of the methodology used to develop the C content coefficients are presented in Annexes 2.1 and 2.2.

8. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 6), the C content of the fuels consumed, and the fraction of C 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).

9. *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

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[32] The source of highway vehicle VMT and fuel consumption is FHWA's VM-1 table. In 2011, FHWA changed its methods for estimating data in the VM-1 table. 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 for the 1990-2010 Inventory and apply to the 2007 to 2013 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[33] See International Bunker Fuels section in this chapter for a more detailed discussion.

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 (2015) and USAF (1998).[34]

- For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2014); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2013).
- For non-road vehicles, activity data were obtained from AAR (2008 through 2013), APTA (2007 through 2013), APTA (2006), BEA (1991 through 2013), Benson (2002 through 2004), DOE (1993 through 2014), DLA Energy (2014), DOC (1991 through 2013), DOT (1991 through 2013), EIA (2009a), EIA (2015), EIA (2002), EIA (1991 through 2014), EPA (2014c), and Gaffney (2007).
- 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 with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (see Annex 3.3). CO_2 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.

Box 3-4: 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 Greenhouse Gas Reporting Program (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 EPA's GHGRP 2010, 2011, 2012, and 2013 reporting years, facility-level fossil fuel combustion emissions reported through the GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau), and associated data available from EIA's 2010 Manufacturing Energy Consumption Survey (MECS). 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 the 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.[35]

This year's 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 Format (CRF) tables that are submitted to the UNFCCC along with this report.[36] However, a full mapping was not completed this year due to fuel category differences between national statistics published by EIA and facility-level reported GHGRP data. Furthermore, given that calendar year 2010 was the first year in which emissions data were reported to EPA's GHGRP, the current inventory's examination only focused on 2010, 2011, 2012 and 2013. For the current exercise, the efforts in reconciling fuels focused on standard, common fuel types (e.g., natural gas, distillate fuel oil, etc.) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information

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[34] 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.

[35] 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/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

[36] See < http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>.

presented in the CRF tables 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. Additionally, in order to expand this effort through the full time series presented in this report, further analyses will be conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data, other available MECS survey years , and any further informative sources of data. 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.

Additionally, to assist in the disaggregation of industrial fuel consumption, EIA will now synthesize energy consumption data using the same procedure as is used for the last historical (benchmark) year of the Annual Energy Outlook (AEO). This procedure reorganizes the most recent data from the Manufacturing Energy Consumption Survey (MECS) (conducted every four years) into the nominal data submission year using the same energy-economy integrated model used to produce the AEO projections, the National Energy Modeling System (NEMS). EIA believes this "nowcasting" technique provides an appropriate estimate of energy consumption for the CRF.

To address gaps in the time series, EIA performs a NEMS model projection, using the MECS baseline sub-sector energy consumption. The NEMS model accounts for changes in factors that influence industrial sector energy consumption, and has access to data which may be more recent than MECS, such as industrial sub-sector macro industrial output (i.e., shipments) and fuel prices. By evaluating the impact of these factors on industrial subsector energy consumption, NEMS can anticipate changes to the energy shares occurring post-MECS and can provide a way to appropriately disaggregate the energy-related emissions data into the CRF.

While the fuel consumption values for the various manufacturing sub-sectors are not directly surveyed for all years, they represent EIA's best estimate of historical consumption values for non-MECS years. Moreover, as an integral part of each AEO publication, this synthetic data series is likely to be maintained consistent with all available EIA and non-EIA data sources even as the underlying data sources evolve for both manufacturing and non-manufacturing industries alike.

Other sectors' fuel consumption (commercial, residential, transportation) will be benchmarked with the latest aggregate values from the Monthly Energy Review.[37] EIA will work with EPA to back cast these values to 1990.

Box 3-5: Carbon Intensity of U.S. Energy Consumption

Fossil fuels are the dominant source of energy in the United States, and CO_2 is the dominant greenhouse gas emitted as a product from their combustion. Energy-related CO_2 emissions are impacted by not only lower levels of energy consumption but also by lowering the C intensity of the energy sources employed (e.g., fuel switching from coal to natural gas). The amount of C emitted from the combustion of fossil fuels is dependent upon the C content of the fuel and the fraction of that C that is oxidized. Fossil fuels vary in their average C 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.[38] In general, the C content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall C 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 3-15 provides a time series of the C intensity for each sector of the U.S. economy. The time series incorporates only the energy consumed from the direct combustion of fossil fuels in each sector. For example, the C intensity for the residential sector does not include the energy from or emissions related to the consumption of electricity for lighting. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest C intensity, which is related to the large percentage of its energy derived from natural gas for heating. The C 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 C intensities over this period. The C intensity of the transportation

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[37] See <http://www.eia.gov/totalenergy/data/monthly/>.

[38] One exajoule (EJ) is equal to 10^{18} joules or 0.9478 QBtu.

sector was closely related to the C content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO_2 Eq./EJ), which were the primary sources of energy. Lastly, the electricity generation sector had the highest C intensity due to its heavy reliance on coal for generating electricity.

Table 3-15: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO_2 Eq./QBtu)

Sector	1990	2005	2009	2010	2011	2012	2013
Residential[a]	57.4	56.6	55.9	55.8	55.8	55.6	55.3
Commercial[a]	59.1	57.5	56.9	56.8	56.6	56.1	55.9
Industrial[a]	64.3	64.3	63.0	62.9	62.4	62.0	61.8
Transportation[a]	71.1	71.4	71.5	71.5	71.5	71.5	71.4
Electricity Generation[b]	87.3	85.8	83.7	83.6	82.9	79.9	81.3
U.S. Territories[c]	73.0	73.4	73.1	73.0	73.1	72.3	72.2
All Sectors[c]	**73.0**	**73.5**	**72.4**	**72.4**	**72.0**	**70.9**	**70.9**

[a] Does not include electricity or renewable energy consumption.

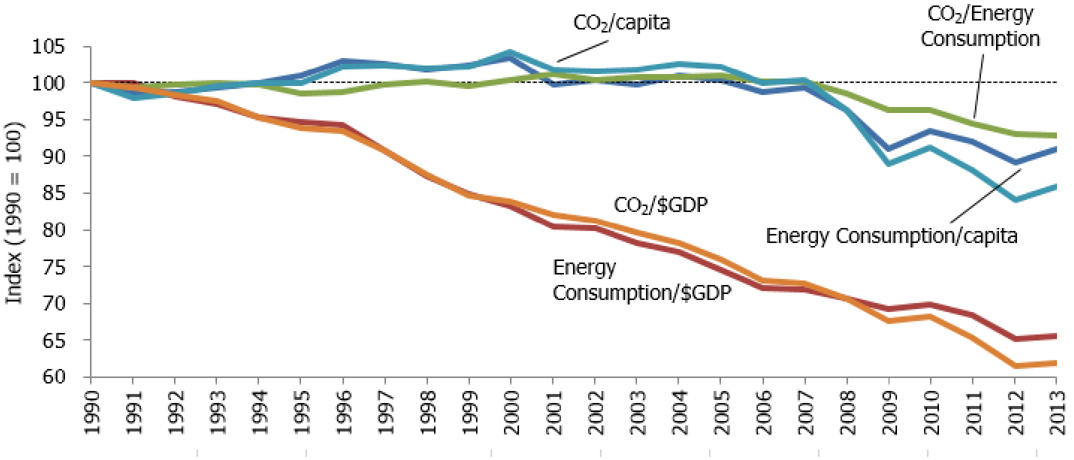
[b] Does not include electricity produced using nuclear or renewable energy.

[c] Does not include nuclear or renewable energy consumption.

Note: Excludes non-energy fuel use emissions and consumption.

Over the twenty-four-year period of 1990 through 2013, however, the C intensity of U.S. energy consumption has been fairly constant, as the proportion of fossil fuels used by the individual sectors has not changed significantly. Per capita energy consumption fluctuated little from 1990 to 2007, but in 2013 was approximately 9.0 percent below levels in 1990 (see Figure 3-14). 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 2014).

Figure 3-14: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



C intensity estimates were developed using nuclear and renewable energy data from EIA (2015), EPA (2010a), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty and Time Series Consistency

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).

Although 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 problems 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 these 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. These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with C 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 the International Bunker Fuels section of this chapter). 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 120 input variables were modeled for CO_2 from energy-related Fossil Fuel Combustion (including about 10 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.[39] 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.[40]

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[39] 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.

[40] 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).[41] 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 3-16. Fossil fuel combustion CO_2 emissions in 2013 were estimated to be between 5,051.0 and 5,403.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 5 percent above the 2013 emission estimate of 5,157.7 MMT CO_2 Eq.

Table 3-16: 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	2013 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[b]	**1,658.1**	**1,600.7**	**1,814.7**	**-3%**	**9%**
Residential	NE	NE	NE	NE	NE
Commercial	3.9	3.7	4.5	-5%	15%
Industrial	75.8	72.2	87.7	-5%	16%
Transportation	NE	NE	NE	NE	NE
Electricity Generation	1,575.0	1,513.3	1,726.4	-4%	10%
U.S. Territories	3.4	3.0	4.1	-12%	19%
Natural Gas[b]	**1,389.5**	**1,374.4**	**1,453.5**	**-1%**	**5%**
Residential	267.2	259.6	285.9	-3%	7%
Commercial	178.2	173.2	190.8	-3%	7%
Industrial	450.8	437.3	483.2	-3%	7%
Transportation	48.8	47.4	52.2	-3%	7%
Electricity Generation	441.9	429.1	464.4	-3%	5%
U.S. Territories	2.6	2.3	3.1	-12%	17%
Petroleum[b]	**2,109.6**	**1,982.0**	**2,232.6**	**-6%**	**6%**
Residential	62.5	59.0	65.7	-6%	5%
Commercial	38.6	36.7	40.3	-5%	4%
Industrial	290.6	236.7	340.7	-19%	17%
Transportation	1,669.6	1,560.6	1,779.5	-7%	7%
Electric Utilities	22.4	21.2	24.4	-5%	9%
U.S. Territories	26.0	24.0	28.8	-8%	11%
Total (excluding Geothermal)[b]	**5,157.3**	**5,050.5**	**5,403.3**	**-2%**	**5%**
Geothermal	0.4	NE	NE	NE	NE
Total (including Geothermal)[b,c]	**5,157.7**	**5,051.0**	**5,403.7**	**-2%**	**5%**

NA (Not Applicable)

NE (Not Estimated)

[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.

[c] Geothermal emissions added for reporting purposes, but an uncertainty analysis was not performed for CO_2 emissions from geothermal production.

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[41] 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.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for CO_2 from fossil fuel combustion was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. 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.

Recalculations Discussion

The Energy Information Administration (EIA 2015) updated energy consumption statistics across the time series relative to the previous Inventory. One such revision is the historical petroleum consumption in the residential sector in 2011 and 2012. These revisions primarily impacted the previous emission estimates from 2010 to 2012; however, additional revisions to industrial and transportation petroleum consumption as well as industrial natural gas and coal consumption impacted emission estimates across the time series. In addition, EIA revised the heat contents of motor gasoline, distillate fuel, and petroleum coke.

For motor gasoline, heating values were previously based on the relative volumes of conventional and reformulated gasoline in the total motor gasoline product supplied to the United States. The revised heating values (first occurring in the January 2015 publication of the Monthly Energy Review) incorporated inputs of ethanol, methyl tert-butyl ether (MTBE) through April 2006, other oxygenates through 2006, and a single national hydrocarbon gasoline blend-stock from 1993 through 2013. Under the previous MER approach, the heating values of conventional and reformulated gasoline were not adjusted for annual variation in the volumes of oxygenates, such as ethanol and MTBE, which have lower heating values than the hydrocarbon components used to produce gasoline. The calculation from the previous EIA Monthly Energy Review publication resulted in overestimated energy values of historic gasoline consumption since 2003, when ethanol use began to grow rapidly. The heating value revision resulted in an historical motor gasoline consumption decrease of approximately 1 percent per year between 1994 through 2012.

Changes to the heat content of distillate fuel resulted in an annual average decrease of approximately 0.1 percent between 1994 through 2012. This decrease was a result of EIA's heat content revision from a constant sulfur content across the time series, to a weighted sulfur content. Additionally, in 2009, EIA began subtracting inputs of renewable diesel fuel from petroleum consumption before converting to energy units. Also, new data from Oak Ridge National Laboratory's Transportation Energy Book (Edition 33) regarding the use of biodiesel in transit buses was incorporated and impacted the distribution of fuel consumption and emissions for on-road buses for the time series starting in 2006.

Petroleum coke consumption decreased by an annual average of approximately 0.1 percent from 2004 to 2012. This decrease was a result of a similar heat content revision in which the EIA recalculated the historically constant petroleum coke heat content to include weighted petroleum coke heat contents (by the two categories of petroleum coke, catalyst and marketable) starting in 2004.

Overall, these changes resulted in an average annual decrease of 9.6 MMT CO_2 Eq. (less than 0.2 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2012, relative to the previous report.

Planned Improvements

To reduce uncertainty of CO_2 from fossil fuel combustion estimates, efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. territories data. This improvement is not all-inclusive, and is part of an ongoing analysis and efforts to continually improve the CO_2 from fossil fuel combustion estimates. In addition, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from this source.

The availability of facility-level combustion emissions through EPA's GHGRP will continue to be examined to help better characterize the industrial sector's energy consumption in the United States, and further classify business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, though 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 UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[42] In line with 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. Additional work will commence to ensure 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 continue to be relied upon.[43]

Another planned improvement is to develop improved estimates of domestic waterborne fuel consumption. 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. It may be possible to more accurately estimate domestic fuel use and emissions by using detailed data on marine ship activity. The feasibility of using domestic marine activity data to improve the estimates is currently being investigated.

CH_4 and N_2O from Stationary Combustion

Methodology

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). Beginning with the current Inventory report, the electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The activity data and emission factors used are described in the following subsections.

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 estimates, wood consumption data for the United States was obtained from EIA's Monthly Energy Review (EIA 2015). Fuel consumption data for coal, natural gas, and fuel oil for the United States were also obtained from EIA's Monthly Energy Review and unpublished supplemental tables on petroleum product detail (EIA 2015). 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 2013) and Jacobs (2010).[44] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[45] Construction and agricultural fuel use

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[42] See <http://unfccc.int/resource/docs/2006/sbsta/eng/09.pdf>.

[43] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

[44] 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.

[45] Though emissions from construction and farm use occur due to both stationary and mobile sources, detailed data was not available to determine the magnitude from each. Currently, these emissions are assumed to be predominantly from mobile sources.

was obtained from EPA (2014). Estimates for wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc., that are reported as biomass by EIA. Tier 1 default emission factors for these three 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 now uses a Tier 2 emission estimation methodology as fuel consumption for the electricity generation sector by control-technology type was obtained from EPA's Acid Rain Program Dataset (EPA 2014a). This combustion technology- and fuel-use data was available by facility from 1996 to 2013 The Tier 2 emission factors used were taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), which in turn are based on emission factors published by EPA.

Since there was a difference between the EPA (2014a) and EIA (2015) total energy consumption estimates, the remaining energy consumption from EIA (2015) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2013.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2014a) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2015) and the ratio of combustion technology and fuel types from EPA (2015). The consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type to the total EIA consumption for each year from 1990 to 1995. Emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific Tier 2 IPCC emission factors.

Lastly, there were significant differences between wood biomass consumption in the electric power sector between the EPA (2014a) and EIA (2015) datasets. The higher wood biomass consumption from EIA (2015) in the electric power sector was distributed to the residential, commercial, and industrial sectors according to their percent share of wood biomass energy consumption calculated from EIA (2015).

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

Uncertainty and Time-Series Consistency

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.[46] For these variables, the uncertainty

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[46] 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

ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[47] 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).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-17. Stationary combustion CH_4 emissions in 2013 (*including* biomass) were estimated to be between 4.6 and 20.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 42 percent below to 157 percent above the 2013 emission estimate of 8.0 MMT CO_2 Eq.[48] Stationary combustion N_2O emissions in 2013 (*including* biomass) were estimated to be between 16.8 and 32.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 27 percent below to 40 percent above the 2013 emissions estimate of 22.9 MMT CO_2 Eq.

Table 3-17: 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	2013 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	8.0	4.6	20.4	-42%	+157%
Stationary Combustion	N_2O	22.9	16.8	32.0	-27%	+40%

[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.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for stationary combustion was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. 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 indirect greenhouse gases from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous Inventories) which results in time-series recalculations

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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.

[47] 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.

[48] 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.

for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in emissions. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Methane and N_2O emissions from stationary sources (excluding CO_2) across the entire time series were revised due revised data from EIA (2015) and EPA (2014a) relative to the previous Inventory. In addition, with the adoption of new GWPs, the entire time series from 1990 through 2012 decreased. The historical data changes resulted in an average annual decrease of 0.3 MMT CO_2 Eq. (4 percent) in CH_4 emissions from stationary combustion and an average annual increase of less than 0.2 MMT CO_2 Eq. (1 percent) in N_2O emissions from stationary combustion for the period 1990 through 2012.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty. 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 since it was expected that the exclusion of biomass from the uncertainty 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 estimates.

Future improvements to the CH_4 and N_2O from Stationary Combustion category involve research into the availability of CH_4 and N_2O from stationary combustion data, and analyzing data reported under EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for CH_4 and N_2O from Stationary Combustion category, particular attention will 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. 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.[49]

CH_4 and N_2O from Mobile Combustion

Methodology

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 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 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 by vehicle and fuel type.[50]

Emission factors for gasoline and diesel on-road vehicles utilizing Tier 2 and Low Emission Vehicle (LEV) technologies were developed by ICF (2006b); all other gasoline and diesel on-road vehicle emissions factors were

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[49] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

[50] 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.

developed by ICF (2004). These factors were derived from EPA, California Air Resources Board (CARB) and Environment Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment Canada tests were designed following the Federal Test Procedure (FTP), which 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 segment 2 were used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts gram per mile emissions of CO_2, CO, HC, NO_x, and PM from vehicles under various conditions, to approximate average driving characteristics.[51]

Emission factors for AFVs were developed by ICF (2006a) after examining Argonne National Laboratory's GREET 1.7–Transportation Fuel Cycle Model (ANL 2006) and Lipman and Delucchi (2002). These sources describe AFV emission factors in terms of ratios to conventional vehicle emission factors. Ratios of AFV to conventional vehicle emissions factors were then applied to estimated Tier 1 emissions factors from light-duty gasoline vehicles to estimate light-duty AFVs. Emissions factors for heavy-duty AFVs were developed in relation to gasoline heavy-duty vehicles. A complete discussion of the data source and methodology used to determine emission factors from AFVs is provided in Annex 3.2.

Annual VMT data for 1990 through 2013 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2014).[52] VMT estimates were then allocated from FHWA's vehicle categories to fuel-specific vehicle categories using the calculated shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (1993 through 2014) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2014). VMT for AFVs were estimated based on Browning (2003) and Browning (2015). The age distributions of the U.S. vehicle fleet were obtained from EPA (2013c, 2000), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2000).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 2007a, 2007b, 2000, 1998, and 1997) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1994a, 1994b, 1998, 1999a) and IPCC (2006).

Non-Road Vehicles

To estimate emissions from non-road vehicles, 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).[53] Activity data were obtained from AAR (2008 through 2013), APTA (2007 through 2013), APTA (2006), BEA (1991 through 2013), Benson (2002 through 2004), DHS (2008), DLA Energy (2014), DOC (1991 through 2013), DOE (1993 through 2013), DOT (1991 through 2013), EIA (2002, 2008, 2007, 2014), EIA (2007 through 2015), EIA (1991 through 2014), EPA (2014d), Esser (2003 through 2004), FAA (2015), FHWA (1996 through 2014), Gaffney (2007), and Whorton (2006 through 2013). Emission factors for non-road modes were taken from IPCC (2006) and Browning (2009).

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[51] Additional information regarding the model can be found online at <http://www.epa.gov/OMS/m6.htm>.

[52] The source of VMT is FHWA's VM-1 table. In 2011, FHWA changed its methods for estimating data in the VM-1 table. 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 for the 2010 Inventory and apply to the 2007-12 time period. This resulted in large changes in VMT by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[53] The consumption of international bunker fuels is not included in these activity data, but is estimated separately under the International Bunker Fuels source category.

Uncertainty and Time-Series Consistency

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 2013 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 and (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 since 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 3.8. 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.

Mobile combustion CH_4 emissions from all mobile sources in 2013 were estimated to be between 1.9 and 2.6 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 13 percent below to 21 percent above the corresponding 2013 emission estimate of 2.1 MMT CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions from mobile sources in 2013 were estimated to be between 16.6 and 22.1 MMT CO_2 Eq., indicating a range of 10 percent below to 20 percent above the corresponding 2013 emission estimate of 18.4 MMT CO_2 Eq.

Table 3-18: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate[a] (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	2.1	1.9	2.6	-13%	+21%
Mobile Sources	N_2O	18.4	16.6	22.1	-10%	+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 analysis. 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.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for mobile combustion was developed and implemented. This plan is based on the IPCC-recommended QA/QC Plan. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. 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 emissions 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

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Increases to CH_4 and N_2O emissions from mobile combustion are largely due to updates made to the Motor Vehicle Emissions Simulator (MOVES 2014) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series. Estimates of alternative fuel vehicle mileage were also revised to reflect updates made to Energy Information Administration (EIA) data on alternative fuel use and vehicle counts. In addition, the alternative fuel vehicle emissions estimates now assume a B100 biodiesel mixture (as opposed to B20, which was used for the previous Inventory report). Overall, these changes resulted in an average annual increase of 0.8 MMT CO_2 Eq. (26 percent) in CH_4 emissions and an average annual decrease of 0.4 MMT CO_2 Eq. (1 percent) in N_2O emissions from mobile combustion for the period 1990 through 2012, relative to the previous report.

Planned Improvements

While the data used for this report represent the most accurate information available, several areas have been identified that could potentially be improved in the near term given available resources.

- Develop improved estimates of domestic waterborne fuel consumption. 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. It may be possible to more accurately estimate domestic fuel use and emissions by using detailed data on marine ship activity. The feasibility of using domestic marine activity data to improve the estimates is currently being investigated. Additionally, the feasibility of including data from a broader range of domestic and international sources for domestic bunker fuels, including data from studies such as the *Third IMO GHG Study 2014*, is being considered.
- Continue to examine the use of EPA's MOVES model in the development of the inventory estimates, including use for uncertainty analysis. Although the Inventory uses some of the underlying data from MOVES, such as vehicle age distributions by model year, MOVES is not used directly in calculating mobile source emissions. The use of MOVES will be further explored.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (IPCC 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, liquefied petroleum gases (LPG), 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 non-energy products such as lubricants, waxes, and asphalt (IPCC 2006).

CO_2 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 60 percent of the total C consumed for non-energy purposes was stored in products, and not released to the atmosphere; the remaining 40 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 NEU 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. In addition, there is some overlap between fossil fuels consumed for non-energy uses and the fossil-derived CO_2 emissions accounted for in the Industrial Processes and Product Use chapter, especially for fuels used as reducing agents. To avoid double-counting, the "raw" non-energy fuel consumption data reported by EIA are modified to account for these overlaps. There are also net exports of petrochemicals 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 C in non-energy applications.

As shown in Table 3-19, fossil fuel emissions in 2013 from the non-energy uses of fossil fuels were 119.8 MMT CO_2 Eq., which constituted approximately 2 percent of overall fossil fuel emissions. In 2013, the consumption of fuels for non-energy uses (after the adjustments described above) was 4,790.7 TBtu, an increase of 7.0 percent since 1990 (see Table 3-20). About 56.2 MMT (205.9 MMT CO_2 Eq.) of the C in these fuels was stored, while the remaining 32.7 MMT C (119.8 MMT CO_2 Eq.) was emitted.

Table 3-19: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO_2 Eq. and percent)

Year	1990	2005	2009	2010	2011	2012	2013
Potential Emissions	312.1	377.5	307.5	325.6	316.4	315.5	325.8
C Stored	194.5	238.6	201.5	211.1	208.0	206.4	205.9
Emissions as a % of Potential	38%	37%	34%	35%	34%	34%	37%
Emissions	**117.7**	**138.9**	**106.0**	**114.6**	**108.4**	**104.9**	**119.8**

Methodology

The first step in estimating C stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The C content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific C content values. Both the non-energy fuel consumption and C content data were supplied by the EIA (2013, 2015) (see Annex 2.1). Consumption of natural gas, LPG, pentanes plus, naphthas, other oils, and special naphtha were adjusted to account for net exports of these products that are not reflected in the raw data from EIA. Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-20 and Table 3-21 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.[54,55] Consumption values were also adjusted to subtract net exports of intermediary chemicals.

For the remaining non-energy uses, the quantity of C 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, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on C stocks and flows were used to develop C storage factors, calculated

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[54] 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.

[55] Some degree of double counting may occur between these estimates of non-energy use of fuels and process emissions from petrochemical production presented in the Industrial Processes and Produce Use sector. Data integration is not feasible at this time as feedstock data from EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries (e.g. petrochemical production) as currently collected through EPA's GHGRP and used for the petrochemical production category.

as the ratio of (a) the C stored by the fuel's non-energy products to (b) the total C 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 this 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 IPCC (2006), which in turn draws from Marland and Rotty (1984).
- For the remaining fuel types (petroleum coke, miscellaneous products, and other petroleum), IPCC does not provide guidance on storage factors, and assumptions were made based on the potential fate of C in the respective NEU products.

Table 3-20: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2009	2010	2011	2012	2013
Industry	**4,215.8**	**5,110.9**	**4,283.0**	**4,572.9**	**4,470.5**	**4,376.7**	**4,619.9**
Industrial Coking Coal	+	80.4	6.4	64.8	60.8	132.5	119.6
Industrial Other Coal	8.2	11.9	11.9	10.3	10.3	10.3	10.3
Natural Gas to Chemical Plants	281.6	260.9	220.3	298.7	297.1	292.6	296.9
Asphalt & Road Oil	1,170.2	1,323.2	873.1	877.8	859.5	826.7	783.3
LPG	1,120.5	1,610.1	1,663.9	1,834.1	1,865.8	1,886.9	2,062.0
Lubricants	186.3	160.2	134.5	149.5	141.8	130.5	138.1
Pentanes Plus	117.6	95.5	61.0	75.3	26.4	40.2	45.4
Naphtha (<401 ° F)	326.3	679.6	451.0	474.6	469.4	432.2	498.5
Other Oil (>401 ° F)	662.1	499.5	392.8	433.2	368.2	267.4	209.0
Still Gas	36.7	67.7	133.9	147.8	163.6	160.6	166.7
Petroleum Coke	27.2	105.2	108.4	+	+	+	+
Special Naphtha	100.9	60.9	44.3	25.3	21.8	14.1	96.5
Distillate Fuel Oil	7.0	11.7	17.5	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	12.2	17.1	15.1	15.3	16.5
Miscellaneous Products	137.8	112.8	151.8	158.7	164.7	161.6	171.2
Transportation	**176.0**	**151.3**	**127.1**	**141.2**	**133.9**	**123.2**	**130.4**
Lubricants	176.0	151.3	127.1	141.2	133.9	123.2	130.4
U.S. Territories	**86.7**	**121.9**	**59.6**	**63.7**	**54.1**	**50.6**	**40.5**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	86.0	117.3	58.5	62.7	53.1	49.5	39.4
Total	**4,478.5**	**5,384.1**	**4,469.6**	**4,777.8**	**4,658.5**	**4,550.5**	**4,790.7**

+ Does not exceed 0.05 TBtu

NA (Not applicable)

Table 3-21: 2013 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	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO_2 Eq.)
Industry	**4,619.9**	**NA**	**85.4**	**NA**	**55.8**	**29.6**	**108.4**
Industrial Coking Coal	119.6	31.00	3.7	0.10	0.4	3.3	12.2
Industrial Other Coal	10.3	25.82	0.3	0.66	0.2	0.1	0.3
Natural Gas to Chemical Plants	296.9	14.47	4.3	0.66	2.8	1.5	5.3
Asphalt & Road Oil	783.3	20.55	16.1	1.00	16.0	0.1	0.3

LPG	2,062.0	17.06	35.2	0.66	23.3	11.9	43.7
Lubricants	138.1	20.20	2.8	0.09	0.3	2.5	9.3
Pentanes Plus	45.4	19.10	0.9	0.66	0.6	0.3	1.1
Naphtha (<401° F)	498.6	18.55	9.2	0.66	6.1	3.1	11.5
Other Oil (>401° F)	209.0	20.17	4.2	0.66	2.8	1.4	5.2
Still Gas	166.7	17.51	2.9	0.66	1.9	1.0	3.6
Petroleum Coke	0.0	27.85	0.0	0.30	0.0	0.0	0.0
Special Naphtha	96.5	19.74	1.9	0.66	1.3	0.6	2.4
Distillate Fuel Oil	5.8	20.17	0.1	0.50	0.1	0.1	0.2
Waxes	16.5	19.80	0.3	0.58	0.2	0.1	0.5
Miscellaneous Products	171.2	20.31	3.5	0.00	0.0	3.5	12.7
Transportation	**130.4**	**NA**	**2.6**	**NA**	**0.2**	**2.4**	**8.8**
Lubricants	130.4	20.20	2.6	0.09	0.2	2.4	8.8
U.S. Territories	**40.5**	**NA**	**0.8**	**NA**	**0.1**	**0.7**	**2.7**
Lubricants	1.0	20.20	0.0	0.09	0.0	0.0	0.1
Other Petroleum (Misc. Prod.)	39.4	20.00	0.8	0.10	0.1	0.7	2.6
Total	**4,790.7**		**88.9**		**56.2**	**32.7**	**119.8**

+ Does not exceed 0.05 TBtu

NA (Not applicable)

[a] To avoid double counting, net exports have been deducted.

Note: Totals may not sum due to independent rounding. Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-19). 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, 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), *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data* (EPA 2015a), *Toxics Release Inventory, 1998* (2000b), *Biennial Reporting System* (EPA 2004, 2009), *Resource Conservation and Recovery Act Information System* (EPA 2013b, 2015b), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011), and the Chemical Data Access Tool (EPA 2012); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013b); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Bureau of the Census (1999, 2004, 2009); Bank of Canada (2012, 2013, 2014); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (1990-2014); Gosselin, Smith, and Hodge (1984); EPA's Municipal Solid Waste (MSW) Facts and Figures (EPA 2013a; 2014a); the Rubber Manufacturers' Association (RMA 2009, 2011, 2014); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001-2013); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); and the American Chemistry Council (ACC 2003-2011, 2012, 2013, 2014a, 2014b). Specific data sources are listed in full detail in Annex 2.3.

Uncertainty and Time-Series Consistency

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 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, LPG, pentanes plus, 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 3-20 and Table 3-21), the storage factors were taken directly from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 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 3-22 (emissions) and Table 3-23 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2013 was estimated to be between 89.0 and 164.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 26 percent below to 38 percent above the 2013 emission estimate of 119.8 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 3-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	73.2	48.8	122.0	-33%	67%
Asphalt	CO_2	0.3	0.1	0.6	-58%	120%
Lubricants	CO_2	18.1	14.9	21.0	-18%	16%
Waxes	CO_2	0.5	0.4	0.8	-27%	59%
Other	CO_2	27.8	16.0	30.1	-42%	8%
Total	**CO_2**	**119.8**	**89.0**	**164.9**	**-26%**	**38%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Table 3-23: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2013 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	66%	53%	72%	-20%	9%
Asphalt	CO_2	100%	99%	100%	0%	0%
Lubricants	CO_2	9%	4%	17%	-57%	90%
Waxes	CO_2	58%	49%	71%	-16%	22%
Other	CO_2	6%	5%	44%	-15%	607%

[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).

In Table 3-23, feedstocks 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—appears to have 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 C 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.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for non-energy uses of fossil fuels was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 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 C (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 for 2011 as well as their trends across the time series.

Petrochemical input data reported by EIA will continue to be investigated in an attempt to address an input/output discrepancy in the NEU model. Since 2001, the C accounted for in the feedstocks C balance outputs (i.e., storage plus emissions) exceeds C inputs. Prior to 2001, the C balance inputs exceed outputs. Starting in 2001 through 2009, outputs exceeded inputs. In 2010 and 2011, inputs exceeded outputs, and in 2012, outputs slightly exceeded inputs. A portion of this discrepancy has been reduced (see Recalculations Discussion, below) and two strategies have been developed to address the remaining portion (see Planned Improvements, below).

Recalculations Discussion

Relative to the previous Inventory, emissions from non-energy uses of fossil fuels decreased by an average of 0.61 MMT CO_2 Eq. (0.2 percent) across the entire time series. The greatest change was an increase of 7 MMT CO_2 Eq. in 2011. The 2014 Guide to the Business of Chemistry contained several new data points for 2008 through 2013, and those values were updated in this Inventory. Additionally, the Rubber Manufacturers Association released a new report with scrap tire characteristics and statistics for 2011 and 2013. Preliminary data for the 2012 Economic Census (U.S. Bureau of the Census 2014) were released which contains data on cleanser shipments in 2012. The hazardous waste data from the Biennial Report (EPA 2015b) provided updated data for 2011, which changed the hazardous waste emissions slightly. EPA's Chemical Data Access Tool (CDAT) (EPA 2014b) was the source of the production data for food additives, antifreeze, and silicones in 2012. Data were interpolated from the latest data point to 2012, to account for this new data source. Import and export data (U.S. International Trade Commission 2014) for synthetic rubber was included in the synthetic rubber stocks in the current inventory.

Planned Improvements

There are several improvements planned for the future:

- More accurate accounting of C in petrochemical feedstocks. EPA has worked with EIA to determine the cause of input/output discrepancies in the C mass balance contained within the NEU model. In the future, two strategies to reduce or eliminate this discrepancy will continue to be pursued. First, accounting of C 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, reconsider the use of top-down C input calculation in estimating emissions will be reconsidered.

Alternative approaches that rely more substantially on the bottom-up C output calculation will be considered instead.

- Response to potential changes in NEU input data. In 2013 EIA initiated implementation of new data reporting definitions for Natural Gas Liquids (NGL) and Liquefied Petroleum Gases (LPG); the new definitions may affect the characterization of the input data that EIA provides for the NEU model and may therefore result in the need for changes to the NEU methodology. EIA also obtains and applies proprietary data for LPG inputs that are not directly applied as NEU input data because the data are proprietary. The potential use of the proprietary data (in an aggregated, non-proprietary form) as inputs to the NEU model will be investigated with EIA.

- 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 C. Additional fates may be researched, including the fossil C 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 (miscellaneous products). A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses. For example, "miscellaneous products" category includes miscellaneous products that are not reported elsewhere in the EIA data set. The EIA does not have firm data concerning the amounts of various products that are being reported in the "miscellaneous products" category; however, EIA has indicated that recovered sulfur from petroleum and natural gas processing, and potentially also C black feedstock could be reported in this category. Recovered sulfur would not be reported in the NEU calculation or elsewhere in the inventory.

- Updating the average C content of solvents was researched, since the entire time series depends on one year's worth of solvent composition data. Unfortunately, the data on C 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 C in solvents. Additional sources of solvents data will be identified in order to update the C content assumptions.

- Updating the average C 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 C content for this category.

- Revising the methodology for consumption, production, and C 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 C 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.

Box 3-6: Reporting of Lubricants, Waxes, and Asphalt and Road Oil Product Use in Energy Sector

The *2006 IPCC Guidelines* 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 Industrial Processes and Product Use (IPPU) sector.[56] In this Inventory, C storage and C 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 (IPCC Source Category 1A).[57]

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. 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., C 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 section 3.2, Table 3-21). For those inputs, U.S. country-specific data on C stocks and flows are used to develop carbon storage factors, which are calculated as the ratio of the C stored by the fossil fuel non-energy products to the total C content of the fuel consumed, taking into account losses in the production process and during product use.[58] The country-specific methodology to reflect national circumstances starts with the aggregate amount of fossil fuels used for non-energy uses and applies a C balance calculation, breaking out the C emissions from non-energy use of lubricants, waxes, and asphalt and road oil. Due to U.S. national circumstances, reporting these C emissions separately under IPPU would involve making artificial adjustments to both the C inputs and C outputs of the non-energy use C balance. These artificial adjustments would also result in the C emissions for lubricants, waxes, and asphalt and road oil being reported under IPPU, while the C storage for lubricants, waxes, and asphalt and road oil would be reported under Energy. To avoid presenting an incomplete C balance and a less transparent approach for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category calculation, the entire calculation of C storage and C emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology, and both the C storage and C emissions for lubricants, waxes, and asphalt and road oil are reported under the Energy sector.

3.3 Incineration of Waste (IPCC Source Category 1A1a)

Incineration 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, Goldstein and Matdes 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 tires. In the United States, almost all incineration of MSW occurs at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Energy chapter. Similarly, tires are combusted for energy recovery in industrial and utility boilers. Incineration of waste results in conversion of the organic inputs to CO_2. According to 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 incineration are calculated by estimating the quantity of waste combusted and the fraction of the waste that is C derived from fossil sources.

Most of the organic materials in municipal solid wastes are of biogenic origin (e.g., paper, yard trimmings), and have their net C flows accounted for under the Land Use, Land-Use Change, and Forestry chapter. However, some components—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

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[56] See Volume 3: Industrial Processes and Product Use, Chapter 5: Non-Energy Products from Fuels and Solvent Use of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

[57] 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*.

[58] Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3: Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion.

goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in municipal solid wastes are predominantly from clothing and home furnishings. As noted above, tires (which contain rubber and carbon black) are also considered a "non-hazardous" waste and are included in the waste incineration estimate, though waste disposal practices for tires differ from municipal solid waste. Estimates on emissions from hazardous waste incineration can be found in Annex 2.3 and are accounted for as part of the C mass balance for non-energy uses of fossil fuels.

Approximately 26.5 million metric tons of MSW were incinerated in the United States in 2013 (EPA 2014). CO_2 emissions from incineration of waste rose 42 percent since 1990, to an estimated 10.1 MMT CO_2 Eq. (10,137 kt) in 2013, as the volume of tires and other fossil C-containing materials in waste increased (see Table 3-24 and Table 3-25). Waste incineration is also a source of CH_4 and N_2O emissions (De Soete 1993, IPCC 2006). CH_4 emissions from the incineration of waste were estimated to be less than 0.05 MMT CO_2 Eq. (less than 0.5 kt CH_4) in 2013, and have not changed significantly since 1990. N_2O emissions from the incineration of waste were estimated to be 0.3 MMT CO_2 Eq. (1 kt N_2O) in 2013, and have not changed significantly since 1990.

Table 3-24: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (MMT CO_2 Eq.)

Gas/Waste Product	1990	2005	2009	2010	2011	2012	2013
CO_2	**8.0**	**12.5**	**11.3**	**11.0**	**10.5**	**10.4**	**10.1**
Plastics	5.6	6.9	5.9	6.0	5.8	5.7	5.7
Synthetic Rubber in Tires	0.3	1.6	1.6	1.5	1.4	1.3	1.2
Carbon Black in Tires	0.4	2.0	1.9	1.8	1.7	1.5	1.4
Synthetic Rubber in MSW	0.9	0.8	0.7	0.7	0.7	0.7	0.7
Synthetic Fibers	0.8	1.2	1.2	1.1	1.1	1.1	1.1
CH_4	+	+	+	+	+	+	+
N_2O	**0.5**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**8.4**	**12.8**	**11.6**	**11.4**	**10.9**	**10.7**	**10.4**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Does not exceed 0.05 MMT.

Table 3-25: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (kt)

Gas/Waste Product	1990	2005	2009	2010	2011	2012	2013
CO_2	**7,972**	**12,454**	**11,295**	**11,026**	**10,550**	**10,363**	**10,137**
Plastics	5,588	6,919	5,946	5,969	5,757	5,709	5,709
Synthetic Rubber in Tires	308	1,599	1,560	1,461	1,363	1,262	1,161
Carbon Black in Tires	385	1,958	1,903	1,783	1,663	1,537	1,412
Synthetic Rubber in MSW	854	765	731	701	712	705	705
Synthetic Fibers	838	1,212	1,155	1,112	1,056	1,149	1,149
CH_4	+	+	+	+	+	+	+
N_2O	**2**	**1**	**1**	**1**	**1**	**1**	**1**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT.

Methodology

Emissions of CO_2 from the incineration of waste include CO_2 generated by the incineration of plastics, synthetic fibers, and synthetic rubber, as well as the incineration of synthetic rubber and carbon black in tires. These emissions were estimated by multiplying the amount of each material incinerated by the C content of the material and the fraction oxidized (98 percent). Plastics incinerated in municipal solid wastes were categorized into seven plastic resin types, each material having a discrete C content. Similarly, synthetic rubber is categorized into three product types, and synthetic fibers were categorized into four product types, each having a discrete C content. Scrap tires contain several types of synthetic rubber, as well as carbon black. Each type of synthetic rubber has a discrete C content, and carbon black is 100 percent C. 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 tires.

More detail on the methodology for calculating emissions from each of these waste incineration sources is provided in Annex 3.7.

For each of the methods used to calculate CO_2 emissions from the incineration of waste, data on the quantity of product combusted and the C content of the product are needed. For plastics, synthetic rubber, and synthetic fibers, the amount of specific materials discarded as municipal solid waste (i.e., the quantity generated minus the quantity recycled) was taken from *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* (EPA 2000 through 2003, 2005 through 2014) and detailed unpublished backup data for some years not shown in the reports (Schneider 2007). For 2013, this data was assumed to be equal to that in 2012, due to the lack of available data. The proportion of total waste discarded that is incinerated was derived from data in BioCycle's "State of Garbage in America" (van Haaren et al. 2010). The most recent data provides the proportion of waste incinerated for 2008, so the corresponding proportion in 2009 through 2013 is assumed to be equal to the proportion in 2008. For synthetic rubber and carbon black in scrap tires, information was obtained from U.S. Scrap Tire Management Summary for 2005 through 2013 data (RMA 2014). Average C contents for the "Other" plastics category and synthetic rubber in municipal solid wastes were calculated from 1998 and 2002 production statistics: C content for 1990 through 1998 is based on the 1998 value; C content for 1999 through 2001 is the average of 1998 and 2002 values; and C content for 2002 to date is based on the 2002 value. Carbon content for synthetic fibers was calculated from 1999 production statistics. Information about scrap tire composition was taken from the Rubber Manufacturers' Association internet site (RMA 2012a).

The assumption that 98 percent of organic C is oxidized (which applies to all waste incineration categories for CO_2 emissions) was reported in EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2006).

Incineration of waste, including MSW, also results in emissions of N_2O and CH_4. These emissions were calculated as a function of the total estimated mass of waste incinerated and an emission factor. As noted above, N_2O and CH_4 emissions are a function of total waste incinerated in each year; for 1990 through 2008, these data were derived from the information published in BioCycle (van Haaren et al. 2010). Data for 2011 were derived from information forthcoming in Themelis and Shin (in press) and Shin (2014). Data on total waste incinerated was not available for 2012 or 2013, so these values were assumed to equal to the 2011 value.

Table 3-26 provides data on municipal solid waste discarded and percentage combusted for the total waste stream. According to Covanta Energy (Bahor 2009) and confirmed by additional research based on ISWA (ERC 2009), all municipal solid waste combustors in the United States are continuously fed stoker units. The emission factors of N_2O and CH_4 emissions per quantity of municipal solid waste combusted are default emission factors for this technology type and were taken from the *2006 IPCC Guidelines* (IPCC 2006).

Table 3-26: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

Year	Waste Discarded	Waste Incinerated	Incinerated (% of Discards)
1990	235,733,657	30,632,057	13.0%
2005	259,559,787	25,973,520	10.0%
2009	270,067,786	23,674,017	8.4%
2010	271,592,991	22,714,122	8.0%
2011	273,116,704	21,741,734	7.6%
2012	273,116,704[a]	20,756,870	7.6%
2013	273,116,704[a]	20,756,870	7.6%

[a] Assumed equal to 2011 value.

Source: van Haaren et al. (2010), Themelis and Shin (in press) and Shin (2014).

Uncertainty and Time-Series Consistency

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. Uncertainty estimates and distributions for waste generation variables (i.e., plastics, synthetic rubber, and textiles generation) were obtained through a conversation with one of the authors of the Municipal Solid Waste in the United States reports. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the other 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 MSW incineration rate; fraction oxidized; missing data on waste composition; average C content of waste components; assumptions on the synthetic/biogenic C ratio; and combustion conditions affecting N_2O emissions. The highest levels of uncertainty surround the variables that are based on assumptions (e.g., percent of clothing and footwear composed of synthetic rubber); the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, C content of C black).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-27. Waste incineration CO_2 emissions in 2013 were estimated to be between 9.1 and 11.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 10 percent below to 13 percent above the 2013 emission estimate of 10.1 MMT CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2013 were estimated to be between 0.2 and 1.3 MMT CO_2 Eq. This indicates a range of 50 percent below to 325 percent above the 2013 emission estimate of 0.3 MMT CO_2 Eq.

Table 3-27: Approach 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	10.1	9.1	11.5	-10%	+13%
Incineration of Waste	N_2O	0.3	0.2	1.3	-50%	+325%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan was implemented for incineration of waste. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. 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 incineration of waste. Trends across the time series were analyzed to determine whether any corrective actions were needed. Actions were taken to streamline the activity data throughout the calculations on incineration of waste.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second*

Assessment Report (SAR) (IPCC 1996) (used in the previous Inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements chapter.

In addition, the data for synthetic rubber and carbon black in scrap tires were updated for 2010 through 2013, based on data obtained from RMA 2013 Scrap Tire Markets Report, which was released in November 2014. This update resulted in an average of a 3 percent decrease of emissions for 2010 through 2012.

The data which calculates the percent incineration was updated in the current inventory. Biocycle has not released a new State of Garbage in America Report since 2010 (with 2008 data), which used to be a semi-annual publication which publishes the results of the nation-wide MSW survey. The results of the survey have been submitted for publishing in Themelis and Shin (in press). This provided updated MSW figures for 2011, so the generation and incineration data for 2009 through 2013 are proxied to the 2011 values.

Planned Improvements

The availability of facility-level waste incineration through EPA's GHGRP will be examined to help better characterize waste incineration operations in the United States. This characterization could include future improvements as to the operations involved in waste incineration for energy, whether in the power generation sector or the industrial sector. Additional examinations will be necessary as, unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines,[59] some facility-level waste incineration emissions reported under the GHGRP may also include industrial process emissions. In line with UNFCCC reporting guidelines, emissions for waste incineration with energy recovery 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 waste incineration 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 ensuring CO_2 emissions from the biomass component of waste are separated in the facility-level reported data, and on maintaining consistency with national waste generation and fate statistics currently used to estimate total, national U.S. greenhouse gas emissions. 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.[60] GHGRP data is available for MSW combustors, which contains information on the CO_2, CH_4, and N_2O emissions from MSW combustion, plus the fraction of the emissions that are biogenic. To calculate biogenic versus total CO_2 emissions, a default biogenic fraction of 0.6 is used. The biogenic fraction will be calculated using the current input data and assumptions to verify the current MSW emission estimates.

Additional improvements will be conducted to improve the transparency in the current reporting of waste incineration. Currently, hazardous industrial waste incineration is included within the overall calculations for the Carbon Emitted from Non-Energy Uses of Fossil Fuels category. Waste incineration activities that do not include energy recovery will also be examined.

3.4 Coal Mining (IPCC Source Category 1B1a)

Three types of coal mining-related activities release CH_4 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. While surface mines account for the majority of U.S. coal

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[59] See <http://unfccc.int/resource/docs/2006/sbsta/eng/09.pdf>.

[60] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

production (see Table 3-30), underground coal mines contribute the largest share of CH_4 emissions (see Table 3-28 and Table 3-29) due to the higher CH_4 content of coal in the deeper underground coal seams. In 2013, 395 underground coal mines and 637 surface mines were operating in the U.S. Also in 2013, the U.S. was the second largest coal producer in the world (891 MMT), after China (3,561 MMT) and followed by India (613 MMT) (IEA 2014).

Underground 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 and depth. Surface coal mines typically produce lower rank coals and remove less than 250 feet of overburden, thus the 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 2013 were estimated to be 64.6 MMT CO_2 Eq. (2,584 kt CH_4), a decline of 33 percent since 1990 (see Table 3-28 and Table 3-29). Of this amount, underground mines accounted for approximately 71.6 percent, surface mines accounted for 15.0 percent, and post-mining emissions accounted for 13.4 percent.

Table 3-28: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
UG Mining	74.2	42.0	59.2	61.6	50.2	47.3	46.2
Liberated	80.8	59.7	78.7	85.2	71.0	65.8	65.8
Recovered & Used	(6.6)	(17.7)	(19.5)	(23.6)	(20.8)	(18.5)	(19.6)
Surface Mining	10.8	11.9	11.5	11.5	11.6	10.3	9.7
Post-Mining (Under Ground)	9.2	7.6	6.7	6.8	6.9	6.7	6.6
Post-Mining (Surface)	2.3	2.6	2.5	2.5	2.5	2.2	2.1
Total	**96.5**	**64.1**	**79.9**	**82.3**	**71.2**	**66.5**	**64.6**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 3-29: CH_4 Emissions from Coal Mining (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
UG Mining	2,968	1,682	2,367	2,463	2,008	1,891	1,849
Liberated	3,234	2,390	3,149	3,406	2,839	2,631	2,633
Recovered & Used	(266)	(708)	(782)	(943)	(831)	(740)	(784)
Surface Mining	430	475	461	461	465	410	388
Post-Mining (UG)	368	306	267	270	276	268	263
Post-Mining (Surface)	93	103	100	100	101	89	84
Total	**3,860**	**2,565**	**3,194**	**3,293**	**2,849**	**2,658**	**2,584**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Methodology

The methodology for estimating CH_4 emissions from coal mining consists of two steps. The first step is to estimate emissions from underground mines. There are two sources of underground mine emissions: ventilation systems and degasification systems. These emissions are estimated on a mine-by-mine basis and then are summed to determine total emissions. The second step of the analysis involves estimating CH_4 emissions from surface mines and post-mining activities. In contrast to 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 from degasification systems. Some mines recover and use the generated 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

Because the U.S. Mine Safety and Health Administration (MSHA) samples CH_4 emissions from ventilation systems for all mines with detectable CH_4 concentrations[61] to ensure miner safety, these mine-by-mine measurements are used to estimate CH_4 emissions from ventilation systems. Since 2011, the EPA has also collected information on ventilation emissions from underground coal mines liberating greater than 36,500,000 actual cubic feet of CH_4 per year (about 14,700 metric tons CO_2 Eq.) through its GHGRP (EPA 2014).[62] Many of the underground coal mines reporting to EPA's GHGRP use the quarterly CH_4 emission data collected by MSHA. However, some mines use their own measurements and samples, which are taken on a quarterly basis. The 2013 ventilation emissions were calculated using the GHGRP data from the mines that take their own measurements and the MSHA data for all other mines.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Some gassier 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. Several data sets were used to estimate the quantity of CH_4 collected by each of the twenty-four mines using degasification systems in 2013. For Alabama mines that sold recovered CH_4 to a pipeline, pipeline sales data published by state petroleum and natural gas agencies were used to estimate degasification emissions. The well data was also used to estimate CH_4 collected from mined-through pre-drainage wells. For most other mines that either sold CH_4 to a pipeline, used CH_4 on site, or vented CH_4 from degasification systems, data on degasification emissions reported to the EPA's GHGRP (EPA 2014) were used.

Step 1.3: Estimate CH_4 Recovered from Degasification Systems and Utilized (Emissions Avoided)

Finally, the amount of CH_4 recovered by degasification and ventilation systems and then used (i.e., not vented) was estimated. In 2013, fifteen active coal mines had CH_4 recovery and use projects, of which thirteen mines sold the recovered CH_4 to a pipeline. One of the mines that sold gas to a pipeline also used CH_4 to fuel a thermal coal dryer. One mine used recovered CH_4 for electrical power generation, and two other mines used recovered CH_4 to heat mine ventilation air or dry coal. Emissions avoided as a result of pipeline sales projects at Alabama and West Virginia mines were estimated using gas sales data reported by the state agencies. For all other mines with pipeline sales or used methane for electric power or heating, either the coal mine operators or project developers supplied information regarding methane recovery or GHGRP data were used.

Step 2: Estimate CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data were 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 (see Table 3-30) (EIA 2014) was multiplied by basin-specific gas contents and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions. The emission factor was revised downward in 2012 from 200 percent, based on more recent studies in Canada and Australia (King 1994, Saghafi 2013). The 150 percent emission factor was applied to all inventory years since 1990, retroactively. For post-mining activities, basin-specific coal production was multiplied by basin-specific gas contents and a 32.5

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[61] 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.

[62] Underground coal mines report to EPA under Subpart FF of the program.

percent emission factor for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific *in situ* gas content data was compiled from AAPG (1984) and USBM (1986). Beginning in 2006, revised data on *in situ* CH_4 content and emission factors have been taken from EPA (1996) and EPA (2005).

Table 3-30: Coal Production (kt)

Year	Underground	Surface	Total
1990	384,244	546,808	931,052
2005	334,398	691,448	1,025,846
2009	301,241	671,475	972,716
2010	305,862	676,177	982,039
2011	313,529	684,807	998,337
2012	310,608	610,307	920,915
2013	309,546	581,270	890,815

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. Because emission estimates from underground ventilation systems were based on actual measurement data from MSHA or EPA's GHGRP, uncertainty is relatively low. A degree of imprecision was introduced because the measurements used were not continuous but rather an average of quarterly instantaneous readings. 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). GHGRP data was used for a number of the mines beginning in 2013, however, the equipment uncertainty is applied to both MSHA and GHGRP data.

Estimates of CH_4 recovered by degasification systems are relatively certain for utilized CH_4 because of the availability of gas sales information. In addition, many coal mine operators provided information on mined-through dates for pre-drainage wells. Many of the 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 avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

Continuous CH_4 monitoring is required of mines that report utilized methane on or off-site to EPA's GHGRP. Beginning in 2013, use of GHGRP data for mines without publicly-available gas usage or sales records has reduced the uncertainty from previous estimations. In addition, since 2012, GHGRP data has been used to estimate CH_4 emissions from vented degasification wells, thus reducing the uncertainty associated with that subsource.

Compared to underground mines, there is considerably more uncertainty associated with surface mining and post-mining emissions because of the difficulty in developing accurate emission factors from field measurements. However, since underground emissions comprise the majority of total coal mining emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-31. Coal mining CH_4 emissions in 2013 were estimated to be between 56.6 and 74.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 12.4 percent below to 15.6 percent above the 2013 emission estimate of 64.6 MMT CO_2 Eq.

Table 3-31: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Coal Mining (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	64.6	56.6	74.7	-12.4%	+15.6%

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Prior to the current Inventory, vented degasification emissions from underground coal mines were typically estimated based on drainage efficiencies reported by either the mining company or MSHA. However, beginning in 2011, underground coal mines began reporting CH_4 emissions from degasification systems to EPA under its GHGRP, which requires degasification quantities to be measured weekly, thus offering a more accurate account than previous methods. As a result, data reported to EPA's GHGRP in 2012 and 2013 were used to estimate vented degasification volumes for those mines. GHGRP data was also used in 2013 for degas-used volumes at mines using methane on-site or without available gas sales records. In addition, for forty-nine mines, the 2013 VAM emission estimates included VAM data measured at least quarterly and reported to the GHGRP. Emissions avoided at mines with VAM mitigation projects (2) were estimated based on emission reductions registered at the Climate Action Reserve GHG Registry (CAR 2014).

Planned Improvements

Future improvements to the Coal Mining category will include continued analysis and integration into the national inventory of the degasification quantities and ventilation emissions data reported by underground coal mines to EPA's GHGRP. A higher reliance on the GHGRP will provide greater consistency and accuracy in future inventories. MSHA data will serve as a quality assurance tool for validating GHGRP data. Reconciliation of the GHGRP and Inventory data sets are still in progress. In implementing improvements and integrating 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 (IPCC 2011).

3.5 Abandoned Underground Coal Mines (IPCC 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 7.2 to 10.8 MMT CO_2 Eq. from 1990 through 2013, 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 (10.8 MMT CO_2 Eq.) due to the large number of mine 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. There were eight gassy mine closures in 2013. In 2013, gross abandoned mine emissions decreased slightly to 8.8 MMT CO_2 Eq. (see Table 3-32 and Table 3-33). Gross emissions are reduced by CH_4 recovered and used at 37 mines, resulting in net emissions in 2013 of 6.2 MMT CO_2 Eq.

Table 3-32: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
Abandoned Underground Mines	7.2	8.4	9.9	9.7	9.3	8.9	8.8
Recovered & Used	+	1.8	3.6	3.2	2.9	2.7	2.6
Total	**7.2**	**6.6**	**6.4**	**6.6**	**6.4**	**6.2**	**6.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-33: CH_4 Emissions from Abandoned Coal Mines (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
Abandoned Underground Mines	288	334	398	389	373	358	353
Recovered & Used	+	70	143	126	116	109	104
Total	**288**	**264**	**254**	**263**	**257**	**249**	**249**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt

Methodology

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, 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 which 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.

In order 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:

$$q = q_i (1 + bD_i t)^{(-1/b)}$$

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/yr
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 emission 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 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. There was not enough data to establish basin-specific equations as was done with the vented, non-flooding mines (EPA 2004).

$$q = q_i e^{(-Dt)}$$

where,

q = Gas flow rate at time t in mmcfd
qi = Initial gas flow rate at time zero (to), mmcfd
D = Decline rate, 1/yr
t = Elapsed time from to (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) account for 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that the 492 abandoned mines closed after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 283 of the 492 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 3-34: Number of Gassy Abandoned Mines Present in U.S. Basins, grouped by Class according to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	33	25	48	106	137	243
Illinois	32	3	14	49	27	76
Northern Appl.	42	22	16	80	36	116
Warrior Basin	0	0	16	16	0	16
Western Basins	27	3	2	32	9	41
Total	**134**	**53**	**96**	**283**	**209**	**492**

Inputs to the decline equation require the average emission rate and the date of abandonment. Generally this data is 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. In addition, 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 emissions 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. Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect ventilation emissions only for pre-1990 closures. CH_4 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 2013. Since the sample of gassy mines (with active mine emissions greater than 100 mcfd) 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 to account for all U.S. abandoned mine emissions.

From 1993 through 2013, emission totals were downwardly adjusted to reflect abandoned mine CH_4 emissions avoided from those mines. The Inventory totals were not adjusted for abandoned mine reductions from 1990 through 1992 because no data was reported for abandoned coal mining CH_4 recovery projects during that time.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted to estimate the uncertainty surrounding the estimates of emissions from abandoned underground coal mines. The uncertainty analysis described below 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 in order 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 3-35. Annual abandoned coal mine CH_4 emissions in 2013 were estimated to be between 5.0 and 7.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20 percent below to 24 percent above the 2013 emission estimate of 6.2 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 after 1972. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH_4 liberation rates exist.

Table 3-35: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	6.2	5.0	7.7	-20%	+24%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

3.6 Petroleum Systems (IPCC Source Category 1B2a)

Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil production, transportation, and refining operations. During each of these activities, CH_4 emissions are released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Fugitive and vented CO_2 emissions from petroleum systems are primarily associated with crude oil production and refining operations but are negligible in transportation operations. Total CH_4 and CO_2 emissions from petroleum systems in 2013 were 25.2 MMT CO_2 Eq. (1,009 kt CH_4)[63] and 6.0 MMT CO_2 Eq. (6,001 kt), respectively. Since 1990, CH_4 emissions have decreased by 20 percent. The net decrease is due mainly to increasing voluntary reductions through Natural Gas STAR in the production segment. From 2012 to 2013, CH_4 emissions increased 8 percent, due mainly to increases in tank venting and pneumatic controller vents. CO_2 emissions have increased by 35 percent since 1990, and 19 percent from 2012 to 2013, due to increased domestic production, with the largest increases occurring in crude refining CO_2 emissions.

Production Field Operations. Production field operations account for 96 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from field operations account for approximately 79 percent of the emissions from the production sector, uncombusted CH_4 emissions (i.e. unburned fuel) account for 11 percent, fugitive emissions are 9 percent, and process upset emissions are approximately 0.3 percent. The most dominant sources of emissions, in order of magnitude, are high bleed pneumatic controllers, oil tanks, shallow water offshore oil platforms, low bleed pneumatic controllers, gas engines, oil wellheads (light crude services), and chemical injection pumps,. These seven sources alone emit 90 percent of the production field operations emissions. Offshore platform emissions are a combination of fugitive, vented, and uncombusted fuel emissions from all equipment housed on oil platforms producing oil and associated gas. Emissions from high and low-bleed pneumatics occur when pressurized gas that is

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[63] The CH_4 emission estimate for 2013 for petroleum systems decreased by approximately 15 MMT CO_2 Eq. from the value presented in the public review draft. This change is largely due to a decrease in the number of pneumatic controllers calculated for the petroleum production segment and an increase in the Natural Gas STAR emissions reductions allocated to petroleum systems (correction of a spreadsheet error noted in the public review draft). For more information, please see Recalculations Discussion.

used for control devices is bled to the atmosphere as they cycle open and closed to modulate the system. Emissions from oil tanks occur when the CH_4 entrained in crude oil under pressure volatilizes once the crude oil is put into storage tanks at atmospheric pressure. Emissions from gas engines are due to unburned CH_4 that vents with the exhaust. Emissions from chemical injection pumps are due to the estimated 25 percent of such pumps that use associated gas to drive pneumatic pumps. The remaining 6 percent of the emissions are distributed among 26 additional activities within the four categories: vented, fugitive, combustion, and process upset emissions. For more detailed, source-level data on CH_4 emissions in production field operations, refer to Annex 3.5.

Since 1990, CH_4 emissions from production of crude oil have decreased by 21 percent. This net decrease is due mainly to increasing voluntary reductions through Natural Gas STAR in the production segment.

Vented CO_2 associated with production field operations account for approximately 99 percent of the total CO_2 emissions from production field operations, while fugitive and process upsets together account for less than 1 percent of the emissions. The most dominant sources of vented CO_2 emissions are oil tanks, high bleed pneumatic controllers, shallow water offshore oil platforms, low bleed pneumatic controllers, and oil wellheads (light crude services). These five sources together account for slightly over 98 percent of the non-combustion CO_2 emissions from production field operations, while the remaining 1 percent of the emissions is distributed among 24 additional activities within the three categories: vented, fugitive, and process upsets. Note that CO_2 from associated gas flaring is accounted in natural gas systems production emissions. CO_2 emissions from flaring for both natural gas and oil were 16 MMT CO_2 Eq. in 2013.

Crude Oil Transportation. Crude oil transportation activities account for approximately 0.7 percent of total CH_4 emissions from the oil industry. Venting from tanks, truck loading, rail loading, and marine vessel loading operations account for 82 percent of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for 14 percent of CH_4 emissions from crude oil transportation. The remaining 4 percent is distributed among two additional sources within the vented emissions category (i.e., pump station maintenance and pipeline pigging). Emissions from pump engine drivers and heaters were not estimated due to lack of data.

Since 1990, CH_4 emissions from transportation have increased by almost 4 percent. However, because emissions from crude oil transportation account for such a small percentage of the total emissions from the petroleum industry, this has had little impact on the overall emissions. Methane emissions have increased by approximately 11 percent from 2012 levels.

Crude Oil Refining. Crude oil refining processes and systems account for slightly above 3 percent of total CH_4 emissions from the oil industry because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is an insignificant amount of CH_4 in all refined products. Within refineries, combustion emissions account for about 60 percent of the CH_4 emissions, while vented and fugitive emissions account for approximately 26 and 13 percent, respectively. Flare emissions are the primary combustion emissions contributor. Refinery system blowdowns for maintenance and process vents are the primary venting contributors. Most of the fugitive CH_4 emissions from refineries are from equipment leaks and storage tanks.

CH_4 emissions from refining of crude oil have increased by approximately 24 percent since 1990; however, similar to the transportation subcategory, this increase has had little effect on the overall emissions of CH_4. Since 1990, CH_4 emissions have fluctuated between 27 and 34 kt.

Flare emissions from crude oil refining accounts for 95 percent of the total CO_2 emissions in petroleum systems. Refinery CO_2 emissions increased by 36 percent from 1990 to 2013.

Table 3-36: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
Production Field Operations (Potential)	**30.8**	**25.1**	**26.3**	**26.9**	**27.6**	**29.6**	**31.3**
Pneumatic controller venting[a]	12.2	10.1	10.6	10.8	11.1	11.6	11.9
Tank venting	6.3	4.7	5.0	5.3	5.5	6.7	7.9
Combustion & process upsets	2.9	2.3	2.4	2.5	2.5	2.7	2.8
Misc. venting & fugitives	7.9	6.9	7.0	7.1	7.1	7.2	7.2
Wellhead fugitives	1.5	1.2	1.3	1.3	1.4	1.5	1.5
Production Voluntary Reductions	(0.1)	(2.6)	(5.7)	(6.4)	(6.6)	(7.3)	(7.1)

Production Field Operations (Net)	**30.8**	**22.6**	**20.6**	**20.6**	**21.1**	**22.3**	**24.2**
Crude Oil Transportation	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**
Refining	**0.7**	**0.8**	**0.7**	**0.7**	**0.8**	**0.8**	**0.8**
Total	**31.5**	**23.5**	**21.5**	**21.3**	**22.0**	**23.3**	**25.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.
[a] Values presented in this table for pneumatic controllers are potential emissions. Net emissions from pneumatic controllers are presented in the Recalculations Discussion.

Table 3-37: CH_4 Emissions from Petroleum Systems (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
Production Field Operations (Potential)	**1,230**	**1,006**	**1,053**	**1,077**	**1,106**	**1,184**	**1,253**
Pneumatic controller venting[a]	489	405	425	433	443	463	474
Tank venting	250	187	202	210	222	267	317
Combustion & process upsets	115	91	95	98	101	107	113
Misc. venting & fugitives	317	275	279	282	284	287	289
Wellhead fugitives	58	47	52	54	56	59	60
Production Voluntary Reductions	(3)	(103)	(227)	(255)	(263)	(290)	(285)
Production Field Operations (Net)	**1,227**	**903**	**826**	**822**	**843**	**893**	**969**
Crude Oil Transportation	**7**	**5**	**5**	**5**	**5**	**6**	**7**
Refining	**27**	**31**	**29**	**27**	**30**	**32**	**34**
Total	**1,261**	**939**	**860**	**854**	**878**	**931**	**1,009**

Note: Totals may not sum due to independent rounding.
[a] Values presented in this table for pneumatic controllers are potential emissions. Net emissions from pneumatic controllers are presented in the Recalculations Discussion.

Table 3-38: CO_2 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
Production Field Operations	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.4**	**0.5**
Pneumatic controller venting	+	+	+	+	+	+	+
Tank venting	0.3	0.2	0.3	0.3	0.3	0.4	0.4
Misc. venting & fugitives	+	+	+	+	+	+	+
Wellhead fugitives	+	+	+	+	+	+	+
Process upsets	+	+	+	+	+	+	+
Crude Refining	**4.1**	**4.6**	**4.4**	**3.8**	**4.1**	**4.7**	**5.5**
Total	**4.4**	**4.9**	**4.7**	**4.2**	**4.5**	**5.1**	**6.0**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 3-39: CO_2 Emissions from Petroleum Systems (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
Production Field Operations	**375**	**285**	**305**	**317**	**333**	**394**	**461**
Pneumatic controller venting	27	23	24	24	25	26	26
Tank venting	328	246	265	276	291	351	417
Misc. venting & fugitives	16	13	14	14	14	14	14
Wellhead fugitives	3	3	3	3	3	3	3
Process upsets	0.2	0.1	0.1	0.2	0.2	0.2	0.2
Crude Refining	**4,070**	**4,620**	**4,351**	**3,836**	**4,134**	**4,666**	**5,540**
Total	**4,445**	**4,904**	**4,656**	**4,153**	**4,467**	**5,060**	**6,001**

Note: Totals may not sum due to independent rounding.

Methodology

The methodology for estimating CH_4 emissions from petroleum systems is based on comprehensive studies of CH_4 emissions from U.S. petroleum systems (GRI/EPA 1996, EPA 1999) and EPA's GHGRP data. The 1996 and 1999 studies calculated emission estimates for 57 activities occurring in petroleum systems from the oil wellhead through crude oil refining, including 33 activities for crude oil production field operations, 11 for crude oil transportation activities, and 13 for refining operations. Annex 3.5 provides greater detail on the emission estimates for these 57 activities. The estimates of CH_4 emissions from petroleum systems do not include emissions downstream of oil refineries because these emissions are negligible.

Key references for activity data and emission factors are DrillingInfo (2014), the Energy Information Administration annual and monthly reports (EIA 1990 through 2014), (EIA 1995 through 2014a, 2014b, 2014c), "Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA" (EPA/GRI 1996a-d), "Estimates of Methane Emissions from the U.S. Oil Industry" (EPA 1999), consensus of industry peer review panels, BOEMRE and BOEM reports (BOEMRE 2004, BOEM 2011), analysis of BOEMRE data (EPA 2005, BOEMRE 2004), the Oil & Gas Journal (OGJ 2014a, 2013b), the Interstate Oil and Gas Compact Commission (IOGCC 2011), the United States Army Corps of Engineers, (1995-2012), and the GHGRP (2010-2013).

The methodology for estimating CH_4 emissions from the 46 oil industry activities (excluding refining activities) employs emission factors initially developed by EPA (1999). Activity data for the years 1990 through 2013 were collected from a wide variety of statistical resources. Emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment item or per activity) by the corresponding activity data (e.g., equipment count or frequency of activity). EPA (1999) provides emission factors for all activities except those related to offshore oil production and field storage tanks. For offshore oil production, two emission factors were calculated using data collected for all federal offshore platforms (EPA 2015, BOEM 2014). One emission factor is for oil platforms in shallow water, and one emission factor is for oil platforms in deep water. Emission factors are held constant for the period 1990 through 2013. The number of platforms in shallow water and the number of platforms in deep water are used as activity data and are taken from Bureau of Ocean Energy Management (BOEM) (formerly Bureau of Ocean Energy Management, Regulation, and Enforcement [BOEMRE]) datasets (BOEM 2011a,b,c). For oil storage tanks, the emissions factor was calculated as the total emissions per barrel of crude charge from E&P Tank data weighted by the distribution of produced crude oil gravities from the HPDI production database (EPA 1999, HPDI 2011).

For some years, complete activity data were not available. In such cases, one of three approaches was employed. Where appropriate, the activity data were calculated from related statistics using ratios developed for EPA (1996). For example, EPA (1996) found that the number of heater treaters (a source of CH_4 emissions) is related to both number of producing wells and annual production. To estimate the activity data for heater treaters, reported statistics for wells and production were used, along with the ratios developed for EPA (1996). In other cases, the activity data were held constant from 1990 through 2013 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable. The CH_4 and CO_2 sources in the production sector share common activity data. See Annex 3.5 for additional detail.

For petroleum refining activities, 2010 to 2013 emissions were directly obtained from EPA's GHGRP. All refineries are required to report their CH_4 and CO_2 emissions for all major activities since 2010. The national totals of these emissions for each activity were used for the 2010 to 2013 emissions. The national emission totals for each activity were also divided by refinery feed rates for those four Inventory years to develop average activity-specific emission factors. These emission factors were used to estimate national emissions for each refinery activity from 1990 to 2009 based on national refinery feed rates for the respective Inventory year. (EPA 2015c).

The Inventory estimate for Petroleum Systems takes into account Natural Gas STAR reductions. Voluntary reductions included in the Petroleum Sector calculations were those reported to Natural Gas STAR for the following activities: artificial lift: gas lift; artificial lift: use compression; artificial lift: use pumping unit; consolidate crude oil production and water storage tanks; lower heater-treater temperature; re-inject gas for enhanced oil recovery; re-inject gas into crude; and route casinghead gas to vapor recovery unit or compressor. In addition, a portion of the total Gas STAR reductions from pneumatic controllers in the production sector are applied to potential emissions in the petroleum sector.

The methodology for estimating CO_2 emissions from petroleum systems combines vented, fugitive, and process upset emissions sources from 29 activities for crude oil production field operations and three activities from petroleum refining. For the production field operations, emissions are estimated for each activity by multiplying emission factors by their corresponding activity data. The 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. One exception to this methodology are the emission factors for crude oil storage tanks, which are obtained from E&P Tank simulation runs, and the emission factor for asphalt blowing, which was derived using the methodology and sample data from API (2009). Other exceptions to this methodology are the three petroleum refining activities (i.e., flares, asphalt blowing, and process vents); the CO_2 emissions data for 2010 to 2013 were directly obtained from the GHGRP. The 2010 to 2013 CO_2 emissions GHGRP data along with the refinery feed data for 2010 to 2013 were used to derive CO_2 emission factors (i.e., sum of activity emissions/sum of refinery feed). The emission factors were then applied to the annual refinery feed to estimate CO_2 emissions for 1990 to 2009.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted in 2010 to determine the level of uncertainty surrounding estimates of emissions from petroleum systems using the IPCC-recommended Approach 2 methodology (Monte Carlo Simulation technique). The @RISK software model was used to quantify the uncertainty associated with the emission estimates using the 7 highest-emitting sources (“top 7 sources”) for the year 1995. The @RISK 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 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 analysis conducted in 2010 has not yet been updated for the 1990 through 2013 Inventory years; instead, the uncertainty percentage ranges calculated previously were applied to 2013 emission estimates. The majority of sources in the current Inventory were calculated using the same emission factors and activity data for which PDFs were developed in the 1990 through 2009 uncertainty analysis. As explained in the Methodology section above and the Recalculations Discussion below, several emission sources have undergone recent methodology revisions, and the 2009 uncertainty ranges will not reflect the uncertainty associated with the recently revised emission factors and activity data sources. Please see discussion on Planned Improvements.

The results presented below provide with 95 percent certainty the range within which emissions from this source category are likely to fall for the year 2013, based on the previously conducted uncertainty assessment using the recommended IPCC methodology. The heterogeneous nature of the petroleum industry makes it difficult to sample facilities that are completely representative of the entire industry. Additionally, highly variable emission rates were measured among many system components, making the calculated average emission rates uncertain. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-40. Petroleum systems CH_4 emissions in 2013 were estimated to be between 19.2 and 62.8 MMT CO_2 Eq., while CO_2 emissions were estimated to be between 4.6 and 14.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 24 percent below to 149 percent above the 2013 emission estimates of 25.2 and 6.0 MMT CO_2 Eq. for CH_4 and CO_2, respectively.

Table 3-40: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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]
Petroleum Systems	CH_4	25.2	19.2	62.8	-24%	149%
Petroleum Systems	CO_2	6.0	4.6	14.9	-24%	149%

[a] Range of 2013 relative uncertainty predicted by Monte Carlo Stochastic Simulation, based on 1995 base year activity factors, for a 95 percent confidence interval.

[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.

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 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification Discussion

The petroleum system 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. In addition, EPA receives feedback through annual expert and public review period. Feedback received is noted in the Recalculations and Planned Improvement sections.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in calculated CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in calculated CO_2 equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories' formal public notice periods, GHGRP data, and new studies. EPA carefully evaluated relevant information available, and made several updates, such as updates to offshore platforms, pneumatic controllers, refineries, and well count data. In addition, revisions to use the latest activity data resulted in changes to emissions for several sources.

Methodological changes made in the current (2015) Inventory are described below.

The net impacts of the changes (comparing 2012 estimate from the previous (2014) Inventory and current (2015) Inventory) are a decrease in CH_4 emissions of around 14.5 MMT CO_2 Eq., or 38 percent, and an increase in CO_2

emissions of around 6 MMT CO_2, or 1,400 percent.[64] Recalculations in the offshore petroleum platforms estimates resulted in a large decrease in 2012 the CH_4 emission estimate from this source in the production segment, from 15.2 MMT CO_2 Eq. in the 2014 Inventory, to 4.7 MMT CO_2 Eq. in the current (2015) Inventory. Recalculations to the onshore petroleum production emissions estimates resulted in a small decrease in the 2012 CH_4 emission estimate for onshore sources, from 22.0 MMT CO_2 Eq. in the previous (2014) Inventory, to 19.5 MMT CO_2 Eq. in the current (2015) Inventory. Methane emission estimates for other segments (i.e., refining and transport) changed by around 0.5 percent. The increase in the CO_2 emissions estimates is due to the update to the petroleum refineries calculations.

Across the 1990-2012 time series, compared to the previous (2014) Inventory, in the current (2015) Inventory, the CH_4 emission estimate decreased by 11.8 MMT CO_2 Eq. on average (or 32 percent), and the CO_2 emission estimate increased by 4.4 MMT CO_2 on average (or around 1,300 percent).

Offshore Platforms

The U.S. Department of the Interior (DOI) began inventorying offshore platform greenhouse gas emissions in the Bureau of Ocean Energy Management's (BOEM) Gulf Offshore Activity Data System (GOADS) in 2000 with subsequent revisions in 2005, 2008, and 2011. The original year 2000 GOADS data were used to develop the emission factors used in the previous GHG Inventory calculations. There have been significant improvements in GOADS data collection and processing since 2000. For the final version of the 1990-2013 Inventory, the 2011 GOADS data were used to revise the emission factors used to calculate offshore oil and gas emissions in the Inventory. The platforms in GOADS were separated into the four categories used in the Inventory methodology: oil versus gas platforms and deep water versus shallow water platforms. Then, the reported emissions for each platform group were used to develop average platform emission factors for Natural Gas Systems and Petroleum Systems. EPA is in the process of calculating emission factors based on the 2005 and 2008 GOADS data that will be applied to years in the time series on either side of the GOADS inventory year that provides the emission factors. Updated activity data were also sought for oil and gas offshore platforms, as the current Inventory activity data is based on DOI 2010 data. At this time no new references were identified that provide current year (2013) and historic platform counts, on a consistent basis. For the year 2012, this revision results in a decrease in CH_4 of 9 MMT CO_2 Eq., or 69 percent and a decrease in CO_2 of >0.1 MMT CO_2, or 24 percent.[65] Commenters on the public review draft supported this update, and recommended that EPA improve its activity data for the number of platforms by using Lexco/OWL, and that EPA improve data on flaring of offshore gas, for example, by reviewing platform data to determine which platforms have a flare.

Well Counts and Completion and Workover Counts

In previous Inventories, data on well counts for petroleum systems were from EIA, while well count data for natural gas systems came from DrillingInfo. In the current GHG Inventory, the time series has been updated to use data from DrillingInfo (HPDI) for producing oil well counts.

The update resulted in an increase in the number of producing oil well counts, which increased calculated potential emissions from sources relying on this activity data. The activity data for many emission sources such as pneumatics, pumps, compressors, separators, and heater treaters are scaled from the 1992 base year, in part based on the ratio of oil well count in a given year to the count of oil wells in 1992. While oil well counts increased by nearly 50 percent on average across all Inventory years, the differential between 1992 and 2012 also slightly increased, leading to an increase in activity data of approximately 6 percent for these sources. For example, the increase in the number of oil wells resulted in an increase in the number of pneumatic controllers estimated in petroleum systems, from around 415,000 for 2012 in the previous Inventory, to around 440,000 in the final current (2015) Inventory.

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[64] Additional information on recent changes to the Inventory can be found at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

[65] For additional information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Revision to Offshore Platform Emissions." EPA (2015b) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

[66,67] Activity data for other emission sources such fugitives from wellheads and headers are calculated by applying activity factors to the count of oil wells; due to the increase in oil well counts for all Inventory years, the activity data for these sources increased by approximately 50 percent up to 150 percent.

Pneumatic Controllers

In previous Inventories, all production segment reductions related to pneumatic controllers that were reported to Natural Gas STAR were assigned to the natural gas systems category. Since some portion of these reductions would be more appropriately assigned to the petroleum systems category, in the final version of the current Inventory, the production segment reductions related to pneumatic controllers have been allocated to the natural gas and petroleum systems categories based upon the calculated potential emissions for pneumatic controllers in each source category. EPA calculated the fraction of potential emissions from pneumatic controllers in petroleum systems out of the total potential pneumatic controller emissions from both natural gas and petroleum systems. On average across all Inventory years, potential pneumatic controller emissions from petroleum systems make up 35 percent of total potential pneumatic controller emissions from both source categories. EPA then applied the year-specific potential emissions fraction to the reported Natural Gas STAR pneumatic controller reductions and allocated that portion of the reductions to the natural gas systems source category. This update decreases net CH_4 emissions by as little as <0.1 MMT CO_2 Eq. in 1990 (1 percent of potential emissions), but reported reductions increase over time such that in 2013 the decrease is 6.3 MMT CO_2 Eq. (over 50 percent of potential emissions). Reviewers supported apportioning the Gas STAR reductions to both oil and gas.

Table 3-41: Pneumatic Controllers Activity Data and Emissions

Data Element	1990	2000	2005	2010	2012	2013
# of Pneumatic Controllers	466,603	395,557	386,058	412,712	441,311	452,170
Calculated Potential Methane (kt)	489	415	405	433	463	474
Natural Gas STAR Reductions (kt)	3	42	67	195	245	254
Net Emissions (kt)	**487**	**373**	**338**	**238**	**218**	**221**

Petroleum Refineries

The calculations for the refineries portion of petroleum systems were revised to use data available from GHGRP subpart Y. All refineries have been reporting to the GHGRP since 2010. For petroleum refining activities, 2010 through 2013 emissions were directly obtained from EPA's GHGRP and used for these years in the Inventory time series. Since GHGRP data only cover recent years of the Inventory time series, an extrapolation approach was employed to develop consistent emissions estimates back to 1990. Publicly available throughput data from DOE/EIA (i.e., refinery feed data from DOE/EIA's Petroleum Supply Annual) were used to scale GHGRP emissions to reflect activity in earlier years. The national emission totals for each activity over the period 2010 through 2013 were divided by total refinery feed rate during 2010 through 2013 to develop average activity-specific emission factors. These emission factors were used to estimate national emissions for each refinery activity from 1990 to 2009 based on national refinery feed rates for the respective Inventory year. The impact of this improvement resulted in an increase in emissions across the time series. For the year 2012, this revision results in an increase in

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[66] For additional information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Revision to Data Source for Well Counts." EPA (2015a) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

[67] The estimate for the number in pneumatic controllers in the petroleum production segment for 2013 decreased 38 percent from the public review draft of the 2015 Inventory to the final 2015 Inventory. This was due to correcting the count of oil wells in the base year 1992, data which drives the pneumatic controller count in later years. The total count of oil wells in 1992 increased, which in turn decreased the difference between 1992 and 2013 well counts from the public review draft and therefore the count of pneumatic controllers from 1992 to 2013 was scaled by a lower factor.

CH_4 of 0.4 MMT CO_2 Eq., or 100 percent, and an increase in CO_2 of 4.7 MMT CO_2, or by a factor of 467.[68] Commenters on the public review draft supported this update.

Planned Improvements

Oil Well Completions and Workovers

The Inventory does not currently distinguish between oil well completions and workovers with hydraulic fracturing and oil well completions and workovers without hydraulic fracturing. In addition, current Inventory emission factors for all oil well completions and workovers were developed using an assumption that all oil well workovers and completions are flared. EPA is seeking data on completions and workovers of oil wells using hydraulic fracturing to better reflect emissions from this rapidly growing and changing sector.

On April 15, 2014, EPA released for external peer review five technical white papers on potentially significant sources of emissions in the oil and gas sector.[69] The white papers focus on technical issues covering emissions and mitigation techniques that target methane and volatile organic compounds (VOCs). The white paper "Emissions from completions and ongoing production of hydraulically fractured oil wells" discussed available data on this source. In addition, EPA's proposed revisions to the GHGRP to add reporting requirements for oil well completions and workovers with hydraulic fracturing would provide EPA with data that could inform updates to the Inventory of U.S. Greenhouse Gas Emissions and Sinks.

Commenters suggested use of data from Allen (2013) to calculate emission factors. A commenter calculated that using an estimate of 7.7 tons CH_4 per completion event and an assumption of 75 percent of new oil wells completed with hydraulic fracturing would increase the current emission estimate for this source by a factor of 400. Commenters suggested that some oil producers voluntarily report completions data to GHGRP and suggested that EPA use this data to develop emission estimates, and then reevaluate these estimates as more data become available.

Pneumatic Controllers

EPA is considering options for updating its estimates for pneumatic controllers in the Inventory. Data sources reviewed include GHGRP (EPA 2014), Allen et al. (2014) and others.[70] Commenters supported the use of direct measurement data to update this emissions source. Commenters supported the use of technology-specific emission factors and categories (e.g., high bleed, intermittent bleed, low bleed, zero bleed) to track emissions and changes in technology. Commenters suggested using GHGRP data on the split between high bleed, intermittent bleed and low bleed to develop data for this approach. A commenter suggested adding a category to address malfunction emissions, which were observed to be substantial in Allen et al. 2014. Commenters supported updating activity data from this source and suggested use of GHGRP data on number of controllers when it becomes available,

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[68] For additional information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Proposed Revision to Refinery Emissions Estimate." EPA (2015c) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

[69] Available online at <http://www.epa.gov/airquality/oilandgas/whitepapers.html>.

[70] For more information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Revisions to Pneumatic Controller Estimates." (EPA 2015d) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

extrapolated to national numbers, or use of data sources such as Allen et al. (2014) or OIPA 2014. EPA is considering these updates for the 2016 GHG Inventory.

Offshore Platforms

EPA is in the process of calculating emission factors based on the 2005 and 2008 GOADS data that will be applied to years in the time series on either side of the GOADS inventory year that provides the emission factors in future versions of the Inventory.[71] Commenters supported this update.

GHGRP

Beginning March 2015, petroleum and natural gas systems reporters to EPA's GHGRP will begin reporting additional data to EPA. The additional data will include, in some cases, information on equipment counts and other additional information that could allow for further improvements to the Inventory.

Commenters on the public review draft recommended that EPA analyze and screen GHGRP data and exclude or correct outliers. Commenters also recommended use of only measured GHGRP data in some cases.

EPA plans to review data reported to GHGRP for potential updates to data and methodology across all segments of petroleum systems.

Other Updates

EPA is evaluating several other sources for potential updates to future inventories.

Abandoned wells are not currently accounted for in the Inventory. EPA is seeking appropriate emission factors and national activity data available to calculate these emissions. Commenters supported including this source category.

EPA received comments process suggesting that bradenhead/casinghead gas emissions may be underestimated in the Inventory. In the Inventory, casinghead gas emissions are calculated using the population of stripper wells and an assumption that 80 percent of stripper wells vent casinghead gas. An emission factor of 2,345 scf CH_4/year per stripper well is applied. Comments on the Inventory noted that casinghead gas emissions are occurring in relatively new and high-production areas. EPA plans to review the method, emission factor, and assumptions used (such as that casinghead emissions occur only at stripper wells) to calculate emissions from casinghead gas in the Inventory. EPA also received comments that associated gas may be underestimated and suggesting use of GHGRP data to calculate associated gas for the Inventory. A commenter suggested that EPA use associated gas venting and flaring data from GHGRP and apply it to the population of associated gas wells in the Inventory to address the concern that casinghead gas emissions occur at a wider set of associated gas wells, not only at stripper wells.

Methane Measurement Studies

Large amounts of data and information are becoming available through EPA's GHGRP and external studies, allowing EPA to re-evaluate and make updates to inventory data. 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 (e.g., EPA's GHGRP, EDF series), and studies that focus on verification of estimates through inverse modeling (e.g., NOAA verification studies). The first type of study can lead to direct improvements to or verification of Inventory estimates. The second type of study can provide general indications on potential over- and under-estimates. EPA reviews both types of studies for data that can inform inventory updates.

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[71] For more information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Offshore Oil and Gas Platform Emission Estimates." (EPA 2015b) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA considers several factors in review of new data for use in the Inventory, including representativeness (national, regional, production-level, emissions-level), availability of data on controls, practices, and other relevant information, availability of relevant activity data, ability to develop emission factors and activity data for the time series, and whether the study includes a robust and transparent sampling approach, measurement method, and key background data.

EPA will continue to review new data from measurement studies, including upcoming data from the EDF series of CH_4 studies, to assess and potentially update Inventory estimates. EPA seeks stakeholder information on studies with data relevant to the Inventory.

Uncertainty

As described in the above section on Uncertainty, EPA calculates uncertainty for the Petroleum Systems source category based on analysis of uncertainty for the seven highest-emitting sources in the Inventory. Since conducting the 2010 uncertainty analysis there have been methodological improvements in two of the seven sources analyzed in 2010. The seven highest-emitting sources (both in the current and in previous inventories) are offshore oil platforms (shallow water), high bleed pneumatics, oil tanks, low bleed pneumatics, gas engines, offshore oil platforms (deep water) and chemical injection pumps. To update the uncertainty analysis to reflect changes that have occurred since 2010, EPA intends to collect updated information on the uncertainties associated with emission and activity factors for the current top 7 emission sources, and reanalyze the uncertainty of the petroleum industry inventory. This analysis will be conducted using the same @RISK model and IPCC methodology applied in the 2010 uncertainty analysis. EPA seeks comment on updated information on uncertainty for the top seven sources and on the approach to calculate uncertainty. For more information, see http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html.

Box 3-7: 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. 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 from naturally-produced CO_2 are estimated based on the 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. The naturally-occurring CO_2 used in EOR operations is assumed to be fully sequestered. Additionally, all anthropogenic CO_2 emitted from natural gas processing and ammonia plants is assumed to be emitted to the atmosphere, regardless of whether the CO_2 is captured or not. These emissions are currently included in the Natural Gas Systems and the Ammonia Production sections of the Inventory report, respectively.

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 emissions estimates for geologic storage.

In the United States, facilities that conduct geologic sequestration of CO_2 and all other facilities that inject CO_2 underground, including facilities conducting EOR, are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities conducting geologic sequestration of CO_2 are required to develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and to report the amount of CO_2 sequestered using a mass balance approach. Data from this program will be evaluated closely and opportunities for improving the emission estimates will be considered.

Preliminary estimates indicate that the amount of CO_2 captured from industrial and natural sites is 46.2 MMT CO_2 Eq. (46,198 kt) (see Table 3-42 and Table 3-43). Site-specific monitoring and reporting data for CO_2 injection sites (i.e., EOR operations) were not readily available, therefore, these estimates assume all CO_2 is emitted. Values for 2011 to 2013 were proxied from 2010 data.

Table 3-42: Potential Emissions from CO_2 Capture and Transport (MMT CO_2 Eq.)

Stage	1990	2005	2009	2010	2011	2012	2013
Acid Gas Removal Plants	4.8	5.8	7.0	11.6	11.6	11.6	11.6
Naturally Occurring CO_2	20.8	28.3	39.7	34.0	34.0	34.0	34.0
Ammonia Production Plants	+	0.7	0.6	0.7	0.7	0.7	0.7
Pipelines Transporting CO_2	+	+	+	+	+	+	+
Total	**25.6**	**34.7**	**47.3**	**46.2**	**46.2**	**46.2**	**46.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-43: Potential Emissions from CO_2 Capture and Transport (kt)

Stage	1990	2005	2009	2010	2011	2012	2013
Acid Gas Removal Plants	4,832	5,798	7,035	11,554	11,554	11,554	11,554
Naturally Occurring CO_2	20,811	28,267	39,725	33,967	33,967	33,967	33,967
Ammonia Production Plants	+	676	580	677	677	677	677
Pipelines Transporting CO_2	8	7	8	8	8	8	8
Total	**25,643**	**34,742**	**47,340**	**46,198**	**46,198**	**46,198**	**46,198**

+ Does not exceed 0.5 kt.

Note: Totals do not include emissions from pipelines transporting CO_2. Totals may not sum due to independent rounding.

3.7 Natural Gas Systems (IPCC 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. Overall, natural gas systems emitted 157.4 MMT CO_2 Eq. (6,295 kt) of CH_4 in 2013, a 12 percent decrease compared to 1990 emissions, and a 2 percent increase compared to 2012 emissions (see Table 3-44, Table 3-45, and Table 3-46) and 37.8 MMT CO_2 Eq. (37,808 kt) of non-combustion CO_2 in 2013, a less than 1 percent increase compared to 1990 emissions, and a 9 percent increase from 2012 emissions (see Table 3-47 and Table 3-48). The 1990 to 2013 decrease in CH_4 emissions is due primarily to the decrease in emissions from distribution and production. The 1990 to 2013 decrease in distribution emissions is due to a decrease in unprotected steel and cast iron pipelines and their replacement with plastic pipelines. The decrease in production emissions is due to increased use of plunger lifts for liquids unloading, regulatory reductions such as reductions from hydraulically fractured gas well completions and workovers resulting from the 2012 New Source Performance Standards (NSPS) for oil and gas, and from a variety of voluntary reduction activities. The 2012 to 2013 increase in CO_2 is due to increased flaring.

CH_4 and non-combustion 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, bleed and discharge emissions from pneumatic controllers, and fugitive 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. Below is a characterization of the four major stages of the natural gas system. Each of the stages is described and the different factors affecting CH_4 and non-combustion CO_2 emissions are discussed.

Field Production. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, gathering pipelines, and well-site gas treatment facilities such as dehydrators and separators. Emissions from pneumatic controllers, kimray pumps, venting for liquids unloading, condensate tanks, pipeline leaks, and offshore platforms account for the majority of CH_4 emissions in 2013. Flaring emissions account for the majority of the non-combustion CO_2 emissions. Emissions from production account for 30 percent of CH_4

emissions and 42 percent of non-combustion CO_2 emissions from natural gas systems in 2013. CH_4 emissions from field production decreased by 21 percent from 1990 to 2013; however, the trend was not stable over the time series—emissions from production generally increased through 2006 due primarily to increases in emissions from pneumatic controllers and hydraulically fractured gas well completions and workovers, and then declined from 2007 to 2013. Reasons for the 2007 to 2013 trend include an increase in plunger lift use for liquids unloading, increased voluntary reductions over that time period (including those associated with pneumatic controllers), and increased reduced emissions completions (RECs) use for well completions and workovers with hydraulic fracturing. CO_2 emissions from production increased 63 percent from 1990 to 2013 due to increases in onshore and offshore flaring.

Processing. In this stage, 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. Fugitive CH_4 emissions from compressors, including compressor seals, are the primary emission source from this stage. The majority of non-combustion CO_2 emissions come from acid gas removal units, which are designed to remove CO_2 from natural gas. Processing plants account for 14 percent of CH_4 emissions and 58 percent of non-combustion CO_2 emissions from natural gas systems. CH_4 emissions from processing increased by 6 percent from 1990 to 2013 as emissions from compressors increased as the quantity of gas produced increased. CO_2 emissions from processing decreased by 22 percent from 1990 to 2013, as a decrease in the quantity of gas processed resulted in a decrease in acid gas removal emissions.

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, which contain large reciprocating and turbine compressors, are used to move the gas throughout the U.S. transmission system. Fugitive CH_4 emissions from these compressor stations, and from pneumatic controllers account for the majority of the emissions from this stage. Uncombusted engine exhaust and pipeline venting are also sources of CH_4 emissions from transmission facilities. 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). Compressors and dehydrators are the primary contributors to emissions from these storage facilities. CH_4 emissions from the transmission and storage sector account for approximately 34 percent of emissions from natural gas systems, while CO_2 emissions from transmission and storage account for less than 1 percent of the non-combustion CO_2 emissions from natural gas systems. CH_4 emissions from this source decreased by 7 percent from 1990 to 2013 due to increased voluntary reductions (e.g., replacement of high bleed pneumatics with low bleed pneumatics). CO_2 emissions from transmission and storage have increased by 5 percent from 1990 to 2013 as the number of compressors has increased.

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 1,252,866 miles of distribution mains in 2013, an increase of nearly 310,000 miles since 1990 (PHMSA 2014). Distribution system emissions, which account for 21 percent of CH_4 emissions from natural gas systems and less than 1 percent of non-combustion CO_2 emissions, result mainly from fugitive 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. Distribution system CH_4 emissions in 2013 were 16 percent lower than 1990 levels (changed from 39.8 MMT CO_2 Eq. to 33.3 MMT CO_2 Eq.), while distribution CO_2 emissions in 2013 were 14 percent lower than 1990 levels (CO_2 emission from this segment are less than 0.1 MMTCO_2 Eq. across the time series).

Total CH_4 emissions for the four major stages of natural gas systems are shown in MMT CO_2 Eq. (Table 3-44) and kt (Table 3-45). Table 3-46 provides additional information on how the estimates in Table 3-44 were calculated. Table 3-46 shows the calculated CH_4 release (i.e. potential emissions before any controls are applied) from each stage, and the amount of CH_4 that is estimated to have been flared, captured, or otherwise controlled, and therefore not emitted to the atmosphere. Subtracting the value for CH_4 that is controlled, from the value for calculated potential release of CH_4, results in the total emissions values. More disaggregated information on potential emissions and emissions is available in Annex 3.6. See Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems.

Table 3-44: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)[a]

Stage	1990	2005	2009	2010	2011	2012	2013
Field Production	59.5	75.5	62.0	56.5	51.3	49.7	47.0
Processing	21.3	16.4	19.2	17.9	21.3	22.3	22.7
Transmission and Storage	58.6	49.1	52.7	51.6	53.9	51.8	54.4
Distribution	39.8	35.4	34.1	33.5	32.9	30.7	33.3
Total	**179.1**	**176.3**	**168.0**	**159.6**	**159.3**	**154.4**	**157.4**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] These values represent CH_4 emitted to the atmosphere. CH_4 that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

Note: Totals may not sum due to independent rounding.

Table 3-45: CH_4 Emissions from Natural Gas Systems (kt)[a]

Stage	1990	2005	2009	2010	2011	2012	2013
Field Production	2,380	3,018	2,482	2,262	2,052	1,989	1,879
Processing	852	655	768	717	851	891	906
Transmission and Storage	2,343	1,963	2,107	2,065	2,154	2,070	2,176
Distribution	1,591	1,417	1,365	1,338	1,315	1,226	1,333
Total	**7,165**	**7,053**	**6,722**	**6,382**	**6,371**	**6,176**	**6,295**

[a] These values represent CH_4 emitted to the atmosphere. CH_4 that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

Note: Totals may not sum due to independent rounding.

Table 3-46: Calculated Potential CH_4 and Captured/Combusted CH_4 from Natural Gas Systems (MMT CO_2 Eq.)

	1990	2005	2009	2010	2011	2012	2013
Calculated Potential[a]	**179.3**	**208.8**	**210.7**	**211.3**	**210.6**	**206.7**	**209.6**
Field Production	59.7	89.8	89.5	90.0	88.4	87.2	85.6
Processing	21.3	20.6	23.0	23.6	25.2	26.2	26.6
Transmission and Storage	58.6	61.7	62.5	62.8	62.7	61.5	63.1
Distribution	39.8	36.6	35.7	34.8	34.3	31.8	34.3
Captured/Combusted	**0.2**	**32.4**	**42.6**	**51.7**	**51.3**	**52.3**	**52.2**
Field Production	0.2	14.4	27.5	33.5	37.1	37.5	38.6
Processing	+	4.2	3.8	5.7	3.9	3.9	3.9
Transmission and Storage	+	12.7	9.8	11.2	8.9	9.8	8.7
Distribution	+	1.2	1.6	1.4	1.5	1.1	1.0
Net Emissions	**179.1**	**176.3**	**168.0**	**159.6**	**159.3**	**154.4**	**157.4**
Field Production	59.5	75.5	62.0	56.5	51.3	49.7	47.0
Processing	21.3	16.4	19.2	17.9	21.3	22.3	22.7
Transmission and Storage	58.6	49.1	52.7	51.6	53.9	51.8	54.4
Distribution	39.8	35.4	34.1	33.5	32.9	30.7	33.3

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding.

+ Emissions are less than 0.1 MMT CO_2 Eq.

[a] In this context, “potential” means the total emissions calculated before voluntary reductions and regulatory controls are applied.

Table 3-47: Non-combustion CO_2 Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Stage	1990	2005	2009	2010	2011	2012	2013
Field Production	9.8	8.1	10.9	10.9	14.0	13.2	15.9
Processing	27.8	21.7	21.2	21.3	21.5	21.5	21.8

Transmission and Storage	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Distribution	+	+	+	+	+	+	+
Total	**37.6**	**30.0**	**32.2**	**32.3**	**35.6**	**34.8**	**37.8**

Note: Totals may not sum due to independent rounding.
+ Emissions are less than 0.1 MMT CO_2 Eq.

Table 3-48: Non-combustion CO_2 Emissions from Natural Gas Systems (kt)

Stage	1990	2005	2009	2010	2011	2012	2013
Field Production	9,775	8,142	10,906	10,883	13,980	13,196	15,947
Processing	27,763	21,746	21,188	21,346	21,466	21,469	21,757
Transmission and Storage	62	64	65	65	65	63	65
Distribution	46	42	41	40	40	37	40
Total	**37,645**	**29,995**	**32,201**	**32,334**	**35,551**	**34,764**	**37,808**

Note: Totals may not sum due to independent rounding.

Methodology

The methodology for natural gas emissions estimates presented in this Inventory involves the calculation of CH_4 and CO_2 emissions for over 100 emissions sources, and then the summation of emissions for each natural gas sector stage.

The calculation of emissions for each source of emissions in natural gas systems generally occurs in three steps:

Step 1. **Calculate Potential Methane –** Collect activity data on production and equipment in use and apply emission factors (i.e., scf gas per unit or activity)

Step 2. Compile Reductions Data – Calculate the amount of the methane that is not emitted, using data on voluntary action and regulations

Step 3. Calculate Net Emissions – Deduct methane that is not emitted from the total methane potential estimates to develop net CH_4 emissions, and calculate CO_2 emissions

This approach of calculating potential CH_4 and then applying reductions data to calculate net emissions was used to ensure an accurate time series that reflects real emission trends. As noted below, key data on emissions from many sources are from a 1996 report containing data collected in 1992. Since the time of this study, practices and technologies have changed. While this study still represents best available data for some emission sources, using these emission factors alone to represent actual emissions without adjusting for emissions controls would in many cases overestimate emissions. As updated emission factors reflecting changing practices are not available for most sources, the 1992 emission factors continue to be used for many sources for all years of the Inventory, but they are considered to be potential emissions factors, representing what emissions would be if practices and technologies had not changed over time.

For the Inventory, the calculated potential emissions are adjusted using data on reductions reported to Natural Gas STAR, and data on regulations that result in CH_4 reductions. As more data become available, alternate approaches may be considered. For example, new data on liquids unloading and on hydraulically fractured gas well completions and workovers enabled EPA to disaggregate or stratify these sources into distinct sub-categories based upon different technology types, each with unique emission factors and activity data.

Step 1. Calculate Potential Methane—Collect activity data on production and equipment in use and apply emission factors

In the first step, potential CH_4 is calculated by multiplying activity data (such as miles of pipeline or number of wells) by factors that relate that activity data to potential CH_4. Potential CH_4 is the amount of CH_4 that would be emitted in the absence of any control technology or mitigation activity. It is important to note that potential CH_4

factors in most cases do not represent emitted CH_4, and must be adjusted for any emissions-reducing technologies, or practices, as appropriate. For more information, please see the Annex.

Potential Methane Factors

The primary basis for estimates of CH_4 and non-combustion-related CO_2 emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute and EPA (EPA/GRI 1996). The EPA/GRI study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The EPA/GRI study was based on a combination of process engineering studies, collection of activity data and measurements at representative gas facilities conducted in the early 1990s. Methane compositions from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001) are adjusted year to year using gross production for oil and gas supply National Energy Modeling System (NEMS) regions from the EIA. Therefore, emission factors may vary from year to year due to slight changes in the CH_4 composition for each NEMS oil and gas supply module region. The majority of emission factors used in the Inventory were derived from the EPA/GRI study. The emission factors used to estimate CH_4 were also used to calculate non-combustion CO_2 emissions. Data from GTI 2001 were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. Additional information about CO_2 content in transmission quality natural gas was obtained from numerous U.S. transmission companies to help further develop the non-combustion CO_2 emission factors.

Although the Inventory primarily uses EPA/GRI emission factors, updates were made to the emissions estimates for several sources in recent Inventories. For liquids unloading, in the 2013 Inventory, the methodology was revised to calculate national emissions through the use region-specific emission factors developed from well data collected in a survey conducted by API/ANGA (API/ANGA 2012). In this methodology, the emission factors used for liquids unloading are not potential factors, but are factors for actual emissions. For gas well completions and workovers (refracturing) with hydraulic fracturing, in this Inventory, EPA used the 2011, 2012, and 2013 GHGRP Subpart W data to stratify the emission sources into four different categories and developed CH_4 emission factors for each category. See the Recalculations Discussion below, and EPA memos “Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Revision to Hydraulically Fractured Gas Well Completions and Workovers Estimate” and “Updating GHG Inventory Estimate for Hydraulically Fractured Gas Well Completions and Workovers” for more information on the methodology for this emission source (EPA 2013d and EPA 2015c).

In addition, in 2015, an update was made to the emission factors applied to offshore platforms. Previously, the Inventory relied on the Bureau of Ocean Energy Management’s (BOEM’s) Gulf Offshore Activity Data System (GOADS) year 2000 inventory to develop emission factors for offshore platforms; the methodology has been updated to use more recent GOADS inventory data to develop emission factors. See the Recalculations Discussion below, and EPA memo “Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Revision to Offshore Platforms Emissions Estimate” (EPA 2015b).

See Annex 3.6 for more detailed information on the methodology and data used to calculate CH_4 and non-combustion CO_2 emissions from natural gas systems.

Updates to emission factors using GHGRP data for natural gas systems and other data continue to be evaluated.

Activity Data

Activity data were taken from the following sources: DrillingInfo, Inc (DrillingInfo 2014); American Gas Association (AGA 1991–1998); Bureau of Ocean Energy Management, Regulation and Enforcement (previous Minerals and Management Service) (BOEMRE 2011a, 2011b, 2011c, 2011d); Natural Gas Liquids Reserves Report (EIA 2005); Natural Gas Monthly (EIA 2014a, 2014b, 2014c); the Natural Gas STAR Program annual emissions savings (EPA 2013c); Oil and Gas Journal (OGJ 1997–2014); Pipeline and Hazardous Materials Safety Administration (PHMSA 2014); Federal Energy Regulatory Commission (FERC 2014); Greenhouse Gas Reporting Program (EPA 2014); other Energy Information Administration data and publications (EIA 2001, 2004, 2012, 2013, 2014). Data for estimating emissions from hydrocarbon production tanks were incorporated (EPA 1999). Coalbed CH_4 well activity factors were taken from the Wyoming Oil and Gas Conservation Commission (Wyoming 2014) and the Alabama State Oil and Gas Board (Alabama 2014).

For a few sources, recent direct activity data are not available. For these sources, either 2012 data was used as proxy for 2013 data, or a set of industry activity data drivers was developed and used to update activity data. 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. For example, recent data on various types of field separation equipment in the production stage (i.e., heaters, separators, and dehydrators) are unavailable. Each of these types of field separation equipment was determined to relate to the number of non-associated gas wells. Using the number of each type of field separation equipment estimated by GRI/EPA in 1992, and the number of non-associated gas wells in 1992, a factor was developed that is used to estimate the number of each type of field separation equipment throughout the time series. More information on activity data and drivers is available in Annex 3.6.

Step 2. Compile Reductions Data—Calculate the amount of the CH_4 that is not emitted, using data on voluntary action and regulations

The emissions calculated in Step 1 above represent potential emissions from an activity, and do not take into account any use of technologies and practices that reduce emissions. To take into account use of such technologies, data, where available, are collected on both regulatory and voluntary reductions. Regulatory actions reducing emissions include National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents and condensate tanks. Voluntary reductions included in the Inventory are those reported to Natural Gas STAR for activities such as replacing a high bleed pneumatic device with a low bleed device, and replacing wet seals with dry seals at reciprocating compressors. For more information on these reductions, please see the Annex. The emission estimates presented in Table 3-44 and Table 3-45 are the CH_4 that is emitted to the atmosphere (i.e., net emissions), not potential emissions without capture or flaring.

The Inventory includes impacts of the New Source Performance Standards (NSPS), which came into effect in October 2012, for oil and gas (EPA 2013b). By separating gas well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific CH_4 emission factors for each category, EPA is implicitly accounting for NSPS reductions from hydraulically fractured gas wells. The NSPS also has VOC reduction requirements for compressors, storage vessels, pneumatic controllers, and equipment leaks at processing plants, which will also impact CH_4 emissions in future Inventories.

Step 3. Calculate Net Emissions—Deduct CH_4 that is not emitted from the total CH_4 potential estimates to develop net CH_4 emissions, and calculate CO_2 emissions

In the final step, emission reductions from voluntary and regulatory actions are deducted from the total calculated potential emissions to estimate the net emissions that are presented in Table 3-44, and included in the Inventory totals. Note that for liquids unloading, condensate tanks, gas well completions and workovers with hydraulic fracturing, and centrifugal compressors, emissions are calculated directly using emission factors that vary by technology and account for any control measures in place that reduce CH_4 emissions. See Annex table A-17 for more information on net emissions for specific sources.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted in 2010 to determine the level of uncertainty surrounding estimates of emissions from natural gas systems using the IPCC-recommended Approach 2 methodology (Monte Carlo Simulation technique). The @RISK software model was used to quantify the uncertainty associated with the emissions estimates using the 12 highest-emitting sources (“top 12 sources”) for the year 2009. The @RISK 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 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 emissions estimates for this category evolves and improves as the underlying methodologies and datasets improve.

The uncertainty analysis conducted in 2010 has not yet been updated for the 1990 through 2013 Inventory years; instead, the uncertainty percentage ranges calculated previously were applied to 2013 emissions estimates. The majority of sources in the current Inventory were calculated using the same emission factors and activity data for which PDFs were developed in the 1990 through 2009 uncertainty analysis. As explained in the Methodology section above and the recalculations discussion below, several emission sources have undergone recent methodology revisions, and the 2009 uncertainty ranges will not reflect the uncertainty associated with the recently revised emission factors and activity data sources. Please see discussion on Planned Improvements.

The results presented below provide with 95 percent certainty the range within which emissions from this source category are likely to fall for the year 2013, based on the previously-conducted uncertainty assessment using the recommended IPCC methodology. The heterogeneous nature of the natural gas industry makes it difficult to sample facilities that are completely representative of the entire industry. Additionally, highly variable emission rates were measured among many system components, making the calculated average emission rates uncertain. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-49. Natural gas systems CH_4 emissions in 2013 were estimated to be between 127.5 and 187.3 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems non-energy CO_2 emissions in 2013 were estimated to be between 30.6 and 49.1 MMT CO_2 Eq. at 95 percent confidence level.

Table 3-49: Approach 2 Quantitative Uncertainty Estimates for CH_4 and Non-energy CO_2 Emissions from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	157.4	127.5	187.3	-19%	+30%
Natural Gas Systems[c]	CO_2	37.8	30.6	49.1	-19%	+30%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

[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 3-45 and Table 3-47.

[c] An uncertainty analysis for the non-energy CO_2 emissions was not performed. The relative uncertainty estimated (expressed as a percent) from the CH_4 uncertainty analysis was applied to the point estimate of non-energy CO_2 emissions.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification Discussion

The natural gas 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. In addition, EPA receives feedback through annual expert and public review periods. Feedback received is noted in the Recalculations and Planned Improvement sections.

Several recent studies have measured emissions at the source level and at the national or regional level (e.g., EDF series of studies) with results that often differ from EPA's estimate of emissions. Commenters to the Inventory noted discrepancies between bottom-up inventory estimates and emissions estimated with satellite and aircraft data. Please see note on Methane Measurement Studies in the Planned Improvements section.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each

greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in calculated CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in calculated CO_2-equivalent emissions from N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories' formal public notice periods, GHGRP data, and new studies. EPA carefully evaluated relevant information available, and made several updates, including revisions to offshore platforms, pneumatic controllers, well counts data, and hydraulically fractured gas well completions and workovers.

In addition, revisions to activity data resulted in changes to emission estimates for several sources. For example, the previous (2014) Inventory used 2011 data as a proxy for condensate production for 2012. The current (2015) Inventory was updated to use the most recent data on condensate production. Large increases in production in the Rocky Mountain and Gulf Coast regions resulted in an increase in calculated 2012 CH_4 emissions from condensate tanks of 0.6 MMT CO_2 Eq., or 15 percent.

The combined impact of all revisions on 2012 natural gas production segment emissions described below, compared to the 2014 Inventory, is a decrease in CH_4 emissions of approximately 0.2 MMT CO_2 Eq., and a decrease in CO_2 emissions of 0.5 MMT, or around 1 percent.[72] Recalculations in the offshore gas platforms estimates resulted in a large decrease in the 2012 CH_4 emission estimate from this source in the production segment, from 7.2 MMT CO_2 Eq. in the previous (2014) Inventory, to 3.8 MMT CO_2 Eq. in the current (2015) Inventory. Recalculations to the onshore gas production emissions estimates resulted in an increase in the 2012 CH_4 emission estimate for onshore sources, from 42.6 MMT CO_2 Eq. in the previous (2014) Inventory, to 46.0 MMT CO_2 Eq. in the current (2015) Inventory. Methane emission estimates for other segments (i.e., processing, transmission and storage, and distribution) changed by less than 0.5 percent.

Across the 1990-2012 time series, compared to the previous (2014) Inventory, in the current (2015) Inventory, the total CH_4 emissions estimate decreased by 5.2 MMT CO_2 Eq. on average (or 3 percent), with the largest decreases in the estimate occurring in early years of the time series; and the CO_2 emissions estimate decreased <0.1 MMT CO_2 on average (<1 percent).

Offshore Platforms

The U.S. Department of the Interior (DOI) began Inventorying offshore platform greenhouse gas emissions in the Bureau of Ocean Energy Management's (BOEM) Gulf Offshore Activity Data System (GOADS) in 2000 with subsequent revisions in 2005, 2008, and 2011. The original year 2000 GOADS data were used to develop the emission factors used in the previous Inventory calculations. There have been significant improvements in GOADS data collection and processing since 2000. For the final version of the 1990-2013 Inventory, the 2011 GOADS data were used to revise the emission factors used to calculate offshore oil and gas emissions in the Inventory. The platforms in GOADS were separated into the four categories used in the GHG Inventory methodology: oil versus gas platforms and deep water versus shallow water platforms. Then, the reported emissions for each platform group were used to develop average platform emission factors for Natural Gas Systems and Petroleum Systems. EPA is in the process of calculating emission factors based on the 2005 and 2008 GOADS data that will be applied to years in the time series on either side of the GOADS inventory year that provides the emission factors in future versions of the Inventory. Updated activity data were also sought for oil and gas offshore platforms, as the current Inventory activity data is based on DOI 2010 data. At this time no new references were identified that provide current year (2013) and historic platform counts, on a consistent basis. The impact of this improvement is a decrease in emissions across the time series. For the year 2012, the CH_4 emissions decrease due to use of revised emission factors is approximately 3.5 MMT CO_2 Eq.[73] Commenters on the public review draft supported this update, and recommended that EPA improve its activity data for the number of platforms by using Lexco/OWL, and that EPA

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[72] Additional information on recent changes to the Inventory can be found at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

[73] For additional information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Revision to Offshore Platform Emissions." EPA (2015b) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

improve data on flaring of offshore gas, for example, by reviewing platform data to determine which platforms have a flare.

Gas Well Completions with Hydraulic Fracturing and Workovers with Hydraulic Fracturing (Refracturing)

In the previous Inventory, completions and workovers from the 2011 and 2012 GHGRP data sets were stratified into four different categories: hydraulic fracturing completions and workovers that vent, flared hydraulic fracturing completions and workovers, hydraulic fracturing completions and workovers with RECs, and hydraulic fracturing completions and workovers with RECs that flare. For each category, 2011 and 2012 GHGRP Subpart W data were used to develop control technology-specific methane emission factors and estimate corresponding activity data for the entire time series.

In the current Inventory, the latest GHGRP data available for 2011, 2012, and 2013 were used to develop updated emission factors for the four categories. The emission factors were applied throughout the time series.

Using the same method as was used in the previous Inventory, a time series of activity data was developed for each category for 1990 through 2013. For RECs, 0 percent was assumed for RECs use from 1990 to 2000; GHGRP RECs percentage was used for 2011, 2012, and 2013; and then linear interpolation was used between the 2000 and 2011 percentages for RECs use. For flaring, 10 percent (the average of the percentage of completions and workovers that were flared in 2011 and 2012 GHGRP data) flaring was assumed from 1990 to 2010 to recognize that some flaring occurred over that time period. For 2011, 2012, and 2013, the GHGRP data on flaring was used. The remaining completions and workovers are assigned to the venting category.

This methodology allows the Inventory to reflect changes in RECs counts and flaring, including those resulting from NSPS Subpart OOOO.

Changes made to the emission factors for gas well completions and workovers with hydraulic fracturing resulted in a decrease in the estimate of CH_4 emissions for all years in the time series. This overall decrease due to the change in the data source is accompanied by declining emissions over time, reflecting impacts of the 2012 NSPS for oil and gas (in effect as of October 2012) which requires control of gas from hydraulically fractured gas well completions and workovers.

This update resulted in a decrease in the emission estimate for 2012 of approximately 2 MMT CO_2 Eq.[74]

Commenters on the Inventory generally supported this update. However, commenters also suggested use of only measured data from GHGRP, removal of outliers from GHGRP, and the consolidation of the emission factors into two categories (controlled versus uncontrolled) instead of four. A commenter suggested removing 2011 data from the GHGRP data used to develop the emission factors for hydraulically fractured gas well completions and workovers. Commenters suggested further subcategorization between completions and workovers.

EPA will consider these comments as it reviews data for this and other GHGRP categories for potential updates in next year’s GHG Inventory.

Natural Gas STAR Reductions

In general, the Inventory continues to use aggregated Natural Gas STAR reductions by natural gas system segment (i.e., production, processing, transmission and storage, and distribution). For some sources, specific emissions reductions activities reported to Natural Gas STAR are matched to potential emissions calculated in the Inventory to calculate net emissions for those sources.

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[74] For additional information on the revisions, please see memo “Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Proposed Revision to Hydraulically Fractured Gas Well Completions and Workovers Estimate.” (EPA 2015c) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

Natural Gas STAR Reductions—Pneumatic Controllers

In previous Inventories, all production segment reductions related to pneumatic controllers that are reported to Natural Gas STAR were assigned to the natural gas systems category. In the final version of the current Inventory, the production segment reductions related to pneumatic controllers have been allocated to the natural gas and petroleum systems categories based upon the calculated potential emissions for pneumatic controllers in each source category. EPA calculated the fraction of potential emissions from pneumatic controllers from natural gas systems out of the total potential pneumatic controller emissions from both natural gas and petroleum systems. On average across all Inventory years, potential pneumatic controller emissions from natural gas systems make up 65 percent of total potential pneumatic controller emissions from both source categories. EPA then applied the year-specific potential emissions fraction to the reported Natural Gas STAR pneumatic controller reductions and allocated that portion of the reductions to the natural gas systems source category. This update resulted in an increase in natural gas CH_4 emissions (increase of approximately 8 MMT CO_2 Eq. from the previous Inventory estimate for 2012) and a decrease in petroleum systems CH_4 emissions.

Table 3-50: Pneumatic Controllers Activity Data and Emissions

Data Element	1990	2000	2005	2010	2012	2013
# of Pneumatic Controllers	233,792	300,408	384,433	466,536	468,466	459,304
Calculated Potential Methane (kt)	539	759	967	1,178	1,185	1,159
Natural Gas STAR Reductions (kt)	3	76	160	530	628	620
Net Emissions (kt)	**537**	**683**	**807**	**647**	**557**	**539**

Well Counts and Completion and Workover Counts

For the public review draft, the time series has been updated with revised well counts and completion and workover counts based on DrillingInfo (HPDI) data. Due to revisions to EPA's processing of DrillingInfo (HPDI) data, well counts across the time series have changed from previous years. For additional information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Revision to Data Source for Well Counts." (EPA 2015a). Commenters to the public review draft suggested that EPA may be overestimating the number of associated gas wells, and that EPA's approach may be inconsistent with EIA and state approaches. See Planned Improvements section on associated gas wells.

For completions and workovers, the Inventory uses GHGRP Subpart W event counts for available years (2011 to 2013) as the activity data basis. Due to the reporting threshold in EPA's GHGRP, using data from EPA's GHGRP alone will not provide a complete national estimate of activity data and emissions. However, the completion and workover counts in GHGRP exceed those calculated using the DrillingInfo data and therefore provide a more complete data set than the DrillingInfo approach. If EPA identifies an opportunity to use DrillingInfo (HPDI) data for improved completion and workover counts for recent years, then activity data and therefore emissions from completions and workovers are expected to increase in years 2011 forward.[75]

Planned Improvements

EPA will continue to refine the emission estimates to reflect the most robust information available. Substantial amounts of new information will be made available in the coming years through a number of channels, including EPA's GHGRP, research studies by various organizations, government and academic researchers, and industry. Relevant ongoing studies are collecting new information related to natural gas system emissions (e.g. Environmental Defense Fund (EDF) study series data on natural gas systems, including new measurements on gathering and boosting, processing, transmission and storage, and distribution). EPA looks forward to reviewing information and data from these studies as they become available for potential incorporation in the Inventory.

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[75] For additional information, please see memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Data Source for Well Counts." EPA (2015a) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

Gas Well Liquids Unloading

EPA is considering updates to its estimates for liquids unloading. Data from a 2012 report published by the American Petroleum Institute (API) and America's Natural Gas Alliance (ANGA) were used beginning with the 1990-2011 Inventory (published 2013) to develop regional activity data and regional emission factors for gas well liquids unloading activities for Natural Gas Systems. EPA is considering how data from GHGRP and Allen et al. (2014a) can be used to update the Inventory estimates for this source.[76] Commenters supported the use of direct measurement data to update this emission source.

Offshore Platforms

EPA is in the process of calculating emission factors based on the 2005 and 2008 GOADS data that will be applied to years in the time series on either side of the GOADS inventory year that provides the emission factors for future versions of the Inventory.[77]

Pneumatic Controllers

EPA is considering options for updating its estimates for pneumatic controllers in the Inventory. Data sources reviewed include EPA's GHGRP (2014), Allen et al. (2014) and others.[78] Commenters supported the use of direct measurement data to update this emissions source. Commenters supported the use of technology-specific emission factors and categories (e.g. high bleed, intermittent bleed, low bleed, zero bleed) to track emissions and changes in technology. Commenters suggested using GHGRP data on the split between high bleed, intermittent bleed and low bleed to develop data for this approach. A commenter suggested adding a category to address malfunction emissions, which were observed to be substantial in Allen et al. 2014b. Commenters supported updating activity data from this source and suggested use of GHGRP data on number of controllers when it becomes available, extrapolated to national numbers, or use of data sources such as Allen et al. (2014b) or OIPA 2014. EPA is considering these updates for the 2016 Inventory.

GHGRP

Beginning March 2015, petroleum and natural gas systems reporters to EPA's GHGRP will begin reporting additional data to EPA. The additional data will include, in some cases, information on equipment counts and other additional information that could allow for further improvements to the Inventory.

Commenters on the public review draft recommended that EPA analyze and screen GHGRP data and exclude or correct outliers. Commenters also recommended use of only measured GHGRP data in some cases.

EPA plans to review data reported to its GHGRP for potential updates to data and methodology across all segments of natural gas systems.

Transmission and Storage

Commenters noted opportunities to update estimates for transmission and storage using data from EPA's GHGRP, noting the use of direct measurements for many sources in transmission and storage. Commenters noted additional

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[76] Please see the memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Revisions to Liquids Unloading Estimates" (EPA 2015e) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

[77] Please see the memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Offshore Oil and Gas Platforms Emissions Estimate" (EPA 2015b) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

[78] For more information, please see the memo "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Revisions to Pneumatic Controller Emission Estimate" (EPA 2015d) available at <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>

sources of data that could potentially be used for Inventory updates include the EDF series (e.g., Colorado State University paper), and a Pipeline Research Council International project.

Commenters suggested reconsidering the approaches used to calculate activity data in transmission and storage. For example, the estimate for national storage facilities is based on residential gas consumption.

EPA will review data from its GHGRP and other sources for potential updates to the data and methods used to calculate emissions from transmission and storage.

Distribution

Commenters recommended revisions to distribution segment emissions estimates. EPA looks forward to reviewing new data on distribution systems (such as data from the EDF series of studies) as they become available.

Commenters suggested updating the approach to estimating M&R station activity data, which is currently based on annual throughput value, which can cause volatility in the annual activity data. EPA plans to review available data for potential updates to this source.

Associated Gas Wells

Commenters to the public review draft of the Inventory suggested that EPA's approach to estimating the number of associated gas wells may overestimate this population. EPA's approach was to include any well with a gas-to-oil ratio (GOR) greater than 0 Mcf/bbl in the associated gas well category. Commenters noted that it is very common for wells that produce mainly oil to also produce a small amount of gas. EPA will investigate alternative thresholds such as a GOR greater than 6 Mcf/bbl for the 2016 Inventory. In addition, EPA will consider whether the emissions source calculations that include associated gas wells should be expanded.

Other Updates

EPA is evaluating several other sources for potential updates to future Inventories.

Abandoned wells are not currently accounted for in the Inventory. EPA is seeking appropriate emission factors and national activity data available to calculate these emissions. Commenters supported including this source category.

Commenters recommended that EPA separate out emissions from gathering and boosting facilities from those from field production sites and noted that upcoming studies and GHGRP data may inform emissions estimates from this source.

Commenters recommended updating production segment fugitive emissions estimates.

Commenters recommended development of emission factors and activity data on a regional as opposed to a national basis.

Methane Measurement Studies

Large amounts of data and information are becoming available through EPA's GHGRP and external studies, allowing EPA to re-evaluate and make updates to Inventory data. 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 (e.g., EPA's GHGRP, EDF series), and studies that focus on verification of estimates through inverse modeling (e.g., NOAA verification studies). The first type of study can lead to direct improvements to or verification of Inventory estimates. The second type of study can provide general indications on potential over- and under-estimates. EPA reviews both types of studies for data that can inform inventory updates.

EPA considers several factors in review of new data for use in the Inventory, including representativeness (national, regional, production-level, emissions-level), availability of data on controls, practices, and other relevant information, availability of relevant activity data, ability to develop emission factors and activity data for the time series, and whether the study includes a robust and transparent sampling approach, measurement method, and key background data

EPA will continue to review new data from measurement studies, including upcoming data from the EDF series of methane studies, to assess and potentially update Inventory estimates. EPA seeks stakeholder information on studies with data relevant to the Inventory.

Uncertainty

As described in the above section on Uncertainty, EPA calculates uncertainty for the Natural Gas Systems source category based on analysis of uncertainty for the twelve highest-emitting sources in the Inventory. Since conducting the 2010 uncertainty analysis there have been methodology improvements in seven of the twelve top sources analyzed in 2010, which have resulted in a shift in which sources make up the top twelve sources list. Sources included in the top twelve methane emissions sources for 2009 were reciprocating compressor fugitives (processing), reciprocating compressor fugitives (transmission), Northeast liquids unloading, Midcentral pneumatic device vents, centrifugal compressors (wet seals, transmission), Midcentral liquids unloading, Rocky Mountain pneumatic device vents, Rocky Mountain gas well workovers with hydraulic fracturing, Rocky Mountain liquids unloading, South West gas well completions with hydraulic fracturing, Gulf Coast liquids unloading, and shallow water gas platforms. Sources in the top twelve methane emissions sources in the current Inventory for year 2013 emissions (without separating sources by region and taking into account Gas STAR reductions, which were not accounted for in the previous assessment) are reciprocating compressor fugitives (transmission), pneumatic device vents (production), reciprocating compressor fugitives (processing), kimray pumps (production), liquids unloading (production), centrifugal compressors (wet seals, processing), condensate tanks (production), pneumatic controllers (transmission), gas engines (processing), reciprocating compressors (storage), fugitives from cast iron steel (distribution), gas engines (production).

In response to the change in the composition of the top twelve sources, EPA intends to collect updated information on the uncertainties associated with emission and activity factors for the current top emission sources, and reanalyze the uncertainty of the natural gas systems inventory. This analysis will be conducted using the same @RISK model and IPCC methodology applied in the 2010 uncertainty analysis. EPA seeks comment on updated information on uncertainty for the top 12 sources and on the approach to calculate uncertainty. For more information, see http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html.

3.8 Energy Sources of Indirect Greenhouse Gas Emissions

In addition to the main greenhouse gases addressed above, many energy-related activities generate emissions of indirect greenhouse gases. Total emissions of nitrogen oxides (NO$_x$), carbon monoxide (CO), and non-CH$_4$ volatile organic compounds (NMVOCs) from energy-related activities from 1990 to 2013 are reported in Table 3-51.

Table 3-51: NO$_x$, CO, and NMVOC Emissions from Energy-Related Activities (kt)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
NO$_x$	**21,106**	**16,602**	**12,798**	**12,004**	**11,796**	**11,051**	**10,557**
Mobile Combustion	10,862	10,295	7,797	7,290	7,294	6,788	6,283
Stationary Combustion	10,023	5,858	4,452	4,092	3,807	3,567	3,579
Oil and Gas Activities	139	321	468	545	622	622	622
Waste Combustion	82	128	81	77	73	73	73
International Bunker Fuels[a]	*1,956*	*1,704*	*1,692*	*1,790*	*1,553*	*1,398*	*1,139*
CO	**125,640**	**64,985**	**44,819**	**45,148**	**44,088**	**42,273**	**40,459**
Mobile Combustion	119,360	58,615	39,256	39,475	38,305	36,491	34,676
Stationary Combustion	5,000	4,648	4,036	4,103	4,170	4,170	4,170
Waste Combustion	978	1,403	1,164	1,084	1,003	1,003	1,003
Oil and Gas Activities	302	318	363	487	610	610	610
International Bunker Fuels[a]	*103*	*133*	*121*	*136*	*137*	*133*	*129*
NMVOCs	**12,620**	**7,191**	**7,200**	**7,464**	**7,759**	**7,449**	**7,139**

Mobile Combustion	10,932	5,724	4,650	4,591	4,562	4,252	3,942
Oil and Gas Activities	554	510	1,894	2,205	2,517	2,517	2,517
Stationary Combustion	912	716	553	576	599	599	599
Waste Combustion	222	241	103	92	81	81	81
International Bunker Fuels[a]	*57*	*54*	*53*	*56*	*51*	*46*	*41*

[a] These values are presented for informational purposes only and are not included in totals.
Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2013 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Emission estimates for 2012 and 2013 for non-EGU and non-mobile sources are held constant from 2011 in EPA (2015). Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual applications from various agencies.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty and Time-Series Consistency

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and accurate estimates of activity data. A quantitative uncertainty analysis was not performed.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

3.9 International Bunker Fuels (IPCC Source Category 1: Memo Items)

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under 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.[79] These decisions are reflected in the IPCC methodological guidance, including the *2006 IPCC Guidelines*, 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).[80]

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[79] 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).

[80] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[81] 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 IPCC Guidelines distinguish between different modes of air traffic. 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 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 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 aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[82]

Emissions of CO_2 from aircraft are essentially a function of fuel use. N_2O 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 considered 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. CO_2 is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2013 from the combustion of international bunker fuels from both aviation and marine activities were 100.7 MMT CO_2 Eq., or 3.6 percent below emissions in 1990 (see Table 3-52 and Table 3-53). Emissions from international flights and international shipping voyages departing from the United States have increased by 72.6 percent and decreased by 47.9 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.

Table 3-52: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990	2005	2009	2010	2011	2012	2013
CO_2	**103.5**	**113.1**	**106.4**	**117.0**	**111.7**	**105.8**	**99.8**
Aviation	38.0	60.1	52.8	61.0	64.8	64.5	65.7
Commercial	*30.0*	*55.6*	*49.2*	*57.4*	*61.7*	*61.4*	*62.8*
Military	*8.1*	*4.5*	*3.6*	*3.6*	*3.1*	*3.1*	*2.9*
Marine	65.4	53.0	53.6	56.0	46.9	41.3	34.1
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation[a]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Marine	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.9**	**1.0**	**0.9**	**1.0**	**1.0**	**0.9**	**0.9**
Aviation	0.4	0.6	0.5	0.6	0.6	0.6	0.6
Marine	0.5	0.4	0.4	0.4	0.4	0.3	0.2
Total	**104.5**	**114.2**	**107.5**	**118.1**	**112.8**	**106.8**	**100.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

[a] CH_4 emissions from aviation are estimated to be zero.

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[81] 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).

[82] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

Table 3-53: CO_2, CH_4 and N_2O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990	2005	2009	2010	2011	2012	2013
CO_2	**103,463**	**113,139**	**106,410**	**116,992**	**111,660**	**105,805**	**99,763**
Aviation	38,034	60,125	52,785	60,967	64,790	64,524	65,664
Marine	65,429	53,014	53,625	56,025	46,870	41,281	34,099
CH_4	**7**	**5**	**5**	**6**	**5**	**4**	**3**
Aviation [a]	0	0	0	0	0	0	0
Marine	7	5	5	6	5	4	3
N_2O	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Aviation	1	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

[a] CH_4 emissions from aviation are estimated to be zero.

Table 3-54: Aviation CO_2 and N_2O Emissions for International Transport (MMT CO_2 Eq.)

Aviation Mode	1990	2005	2009	2010	2011	2012	2013
Commercial Aircraft	30.0	55.6	49.2	57.4	61.7	61.4	62.8
Military Aircraft	8.1	4.5	3.6	3.6	3.1	3.1	2.9
Total	**38.0**	**60.1**	**52.8**	**61.0**	**64.8**	**64.5**	**65.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Methodology

Emissions of CO_2 were estimated by applying C content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under CO_2 from Fossil Fuel Combustion. Carbon content and fraction oxidized factors for jet fuel, distillate fuel oil, and residual fuel oil were taken directly from EIA and are presented in Annex 2.1, Annex 2.2, and Annex 3.8 of this Inventory. Density conversions were taken from Chevron (2000), ASTM (1989), and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2015) and USAF (1998), and heat content for jet fuel was taken from EIA (2015). 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 *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following values, in units of grams of pollutant per kilogram of fuel consumed (g/kg), were 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: 0.32 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, 2000 through 2013 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 2013 are obtained from FAA's AEDT model (FAA 2015). The radar-informed method that was used to estimate CO_2 emissions for commercial aircraft for 1990, and 2000 through 2013 is not possible for 1991 through 1999 because the radar data set is not available for years prior to 2000. FAA developed 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.

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 2014). 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 3-55. See Annex 3.8 for additional discussion of military data.

Activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were taken from unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 2011) for 1990 through 2001, 2007 through 2011, 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 (2014). 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 3-56.

Table 3-55: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
U.S. and Foreign Carriers	3,222	5,983	5,293	6,173	6,634	6,604	6,748
U.S. Military	862	462	367	367	319	321	294
Total	**4,084**	**6,445**	**5,660**	**6,540**	**6,953**	**6,925**	**7,042**

Note: Totals may not sum due to independent rounding.

Table 3-56: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
Residual Fuel Oil	4,781	3,881	4,040	4,141	3,463	3,069	2,537
Distillate Diesel Fuel & Other	617	444	426	476	393	280	235
U.S. Military Naval Fuels	522	471	374	448	382	381	308
Total	**5,920**	**4,796**	**4,841**	**5,065**	**4,237**	**3,730**	**3,081**

Note: Totals may not sum due to independent rounding.

Uncertainty and Time-Series Consistency

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.[83] 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, and in the activity data on military operations and training that were used to estimate percentages of total fuel use reported as bunker fuel emissions. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the Navy and Air Force from the Defense Logistics Agency. These data may slightly over or under estimate actual total fuel use in aircraft and ships because each Service may have procured fuel from, and/or may have sold to, traded with, and/or given fuel to other ships, aircraft, governments, or other entities. There are uncertainties in 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 2001. 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, Department and military Service 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 additional data collection.

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.[84]

There is also concern regarding the reliability of the existing DOC (2013) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

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[83] See uncertainty discussions under Carbon Dioxide Emissions from Fossil Fuel Combustion.

[84] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site, 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. The estimates in Mobile Combustion are also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

QA/QC and Verification

A source-specific QA/QC plan for international bunker fuels was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. 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 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

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous Inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

In addition, changes to emission estimates are due to revisions made to historical activity data for military aircraft consumption from DLA Energy 2014. These historical data changes resulted in changes to the emission estimates for the most recent inventory year compared to the previous Inventory. This equaled a decrease in emissions from international bunker fuels of less than 0.1 MMT CO_2 Eq. (less than 0.01 percent) in total emissions in 2012.

Planned Improvements

The feasibility of including data from a broader range of domestic and international sources for bunker fuels, including data from studies such as the Third IMO GHG Study 2014, is being considered.

3.10 Wood Biomass and Ethanol Consumption (IPCC Source Category 1A)

The combustion of biomass fuels such as wood, charcoal, and wood waste and biomass-based fuels such as ethanol 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 UNFCCC, CO_2 emissions from biomass 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 (C) fluxes from changes in biogenic C 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.

In 2013, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 208.6 MMT CO_2 Eq. (208,594 kt) (see Table 3-57 and Table 3-58). As the largest consumer of woody biomass, the industrial sector was responsible for 57.6 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 28.7 percent of the total, while the commercial and electricity generation sectors accounted for the remainder.

Table 3-57: CO_2 Emissions from Wood Consumption by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Industrial	135.3	136.3	110.6	119.5	122.9	125.7	120.2
Residential	59.8	44.3	51.6	45.4	46.4	43.3	59.8
Commercial	6.8	7.2	7.5	7.4	7.1	6.3	7.2
Electricity Generation	13.3	19.1	18.6	20.2	18.8	19.6	21.3
Total	**215.2**	**206.9**	**188.2**	**192.5**	**195.2**	**194.9**	**208.6**

Note: Totals may not sum due to independent rounding.

Table 3-58: CO_2 Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Industrial	135,348	136,269	110,610	119,537	122,865	125,724	120,202
Residential	59,808	44,340	51,558	45,371	46,402	43,309	59,808
Commercial	6,779	7,218	7,486	7,385	7,131	6,257	7,241
Electricity Generation	13,252	19,074	18,566	20,169	18,784	19,612	21,344
Total	**215,186**	**206,901**	**188,220**	**192,462**	**195,182**	**194,903**	**208,594**

Note: Totals may not sum due to independent rounding.

The transportation sector is responsible for most of the ethanol consumption in the United States. Ethanol 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 2013, the United States consumed an estimated 1,091.8 trillion Btu of ethanol, and as a result, produced approximately 74.7 MMT CO_2 Eq. (74,743 kt) (see Table 3-59 and Table 3-60) of CO_2 emissions. Ethanol 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 3-59: CO_2 Emissions from Ethanol Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Transportation	4.1	22.4	61.2	71.3	71.5	71.5	73.4
Industrial	0.1	0.5	0.9	1.1	1.1	1.1	1.2
Commercial	+	0.1	0.2	0.2	0.2	0.2	0.2
Total	**4.2**	**22.9**	**62.3**	**72.6**	**72.9**	**72.8**	**74.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-60: CO_2 Emissions from Ethanol Consumption (kt)

End-Use Sector	1990	2005	2009	2010	2011	2012	2013
Transportation[a]	4,136	22,414	61,193	71,287	71,537	71,510	73,354
Industrial	56	468	885	1,134	1,146	1,142	1,206
Commercial	34	60	193	226	198	175	183
Total	**4,227**	**22,943**	**62,272**	**72,647**	**72,881**	**72,827**	**74,743**

[a] See Annex 3.2, Table A-92 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

Methodology

Woody biomass emissions were estimated by applying two EIA gross heat contents (Lindstrom 2006) to U.S. consumption data (EIA 2014) (see Table 3-61), provided in energy units for the industrial, residential, commercial, and electric generation 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. It was assumed that the woody biomass contains black liquor and other wood wastes, has a moisture content of 12 percent, and is converted into CO_2 with 100 percent efficiency. The emissions from ethanol consumption were calculated by applying an emission factor of 18.67 MMT C/QBtu (EPA 2010) to U.S. ethanol consumption estimates that were provided in energy units (EIA 2015) (see Table 3-62).

Table 3-61: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990		2005		2009	2010	2011	2012	2013
Industrial	1,441.9		1,451.7		1,178.4	1,273.5	1,308.9	1,339.4	1,280.6
Residential	580.0		430.0		500.0	440.0	450.0	420.0	580.0
Commercial	65.7		70.0		72.6	71.6	69.2	60.7	70.2
Electricity Generation	128.5		185.0		180.0	195.6	182.2	190.2	207.0
Total	**2,216.2**		**2,136.7**		**1,931.0**	**1,980.7**	**2,010.2**	**2,010.3**	**2,137.8**

Note: Totals may not sum due to independent rounding.

Table 3-62: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990		2005		2009	2010	2011	2012	2013
Transportation	60.4		327.4		893.9	1,041.4	1,045.0	1,044.6	1,071.5
Industrial	0.8		6.8		12.9	16.6	16.7	16.7	17.6
Commercial	0.5		0.9		2.8	3.3	2.9	2.6	2.7
Total	**61.7**		**335.1**		**909.7**	**1,061.2**	**1,064.6**	**1,063.8**	**1,091.8**

Note: Totals may not sum due to independent rounding.

Uncertainty and Time-Series Consistency

It is assumed that the combustion efficiency for woody biomass is 100 percent, which is believed to be an overestimate of the efficiency of wood combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates. 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 production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Wood consumption values were revised relative to the previous Inventory for 2012 based on updated information from EIA's *Monthly Energy Review* (EIA 2015). These revisions of historical data for wood biomass consumption resulted in an average annual increase in emissions from wood biomass consumption of less than 0.1 MMT CO_2 Eq. (less than 0.1 percent) from 1990 through 2012. Total overall ethanol consumption values remained constant relative to the previous inventory for 2012, although there were small differences in historical consumption among the industrial, transportation, and commercial sectors. Consumption increased within the industrial sector and decreased in the transportation and commercial sectors (EIA 2015), resulting in changes less than 0.1 MMT CO_2 Eq. (less than 0.1 percent) from 1990 through 2012.

Planned Improvements

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 business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, though 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 UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[85] In line with 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.[86]

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[85] See <http://unfccc.int/resource/docs/2006/sbsta/eng/09.pdf>.

[86] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

4. Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. This chapter includes sources of emissions formerly represented in the 'Industrial Processes' and 'Solvent and Other Product Use' chapters in prior versions of this report. The industrial processes and product use categories included in this chapter are presented in Figure 4-1.

Greenhouse gas emissions are produced as the by-products of various non-energy-related industrial activities. That is, these emissions are produced either from 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), and nitrous oxide (N_2O). The processes included in this chapter include iron and steel production and metallurgical coke production, cement production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), ammonia production and urea consumption, petrochemical production, aluminum production, soda ash production and use, titanium dioxide production, CO_2 consumption, ferroalloy production, glass production, zinc production, phosphoric acid production, lead production, silicon carbide production and consumption, nitric acid production, and adipic acid production.

In addition, greenhouse gases are often used in products or by end-consumers. These gases include industrial sources of man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and nitrous oxide (N_2O). 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 accumulate in the atmosphere as long as emissions continue. 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 is growing rapidly since they are the primary substitutes for ozone depleting substances (ODSs), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer. HFCs, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States such as aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. N_2O is emitted by the production of adipic acid and nitric acid, semiconductor manufacturing, end-consumers in product uses through the administration of anesthetics, and by industry as a propellant in aerosol products.

In 2013, IPPU generated emissions of 359.1 million metric tons of CO_2 equivalent (MMT CO_2 Eq.),[147] or 5.4 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 163.0 MMT CO_2 Eq. (162,979 kt) in 2013, or 3.0 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.8 MMT CO_2 Eq. (32 kt) in 2013, which was less than 1 percent of U.S. CH_4 emissions. N_2O emissions from IPPU were 19.1 MMT CO_2 Eq. (64 kt) in 2013, or 5.4 percent of total U.S. N_2O emissions. In 2013 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 176.3 MMT CO_2 Eq. Total emissions from IPPU in 2013 were 5.0 percent more than 1990 emissions. Indirect greenhouse gas emissions also result from IPPU, and are presented in Table 4-106 in kilotons (kt).

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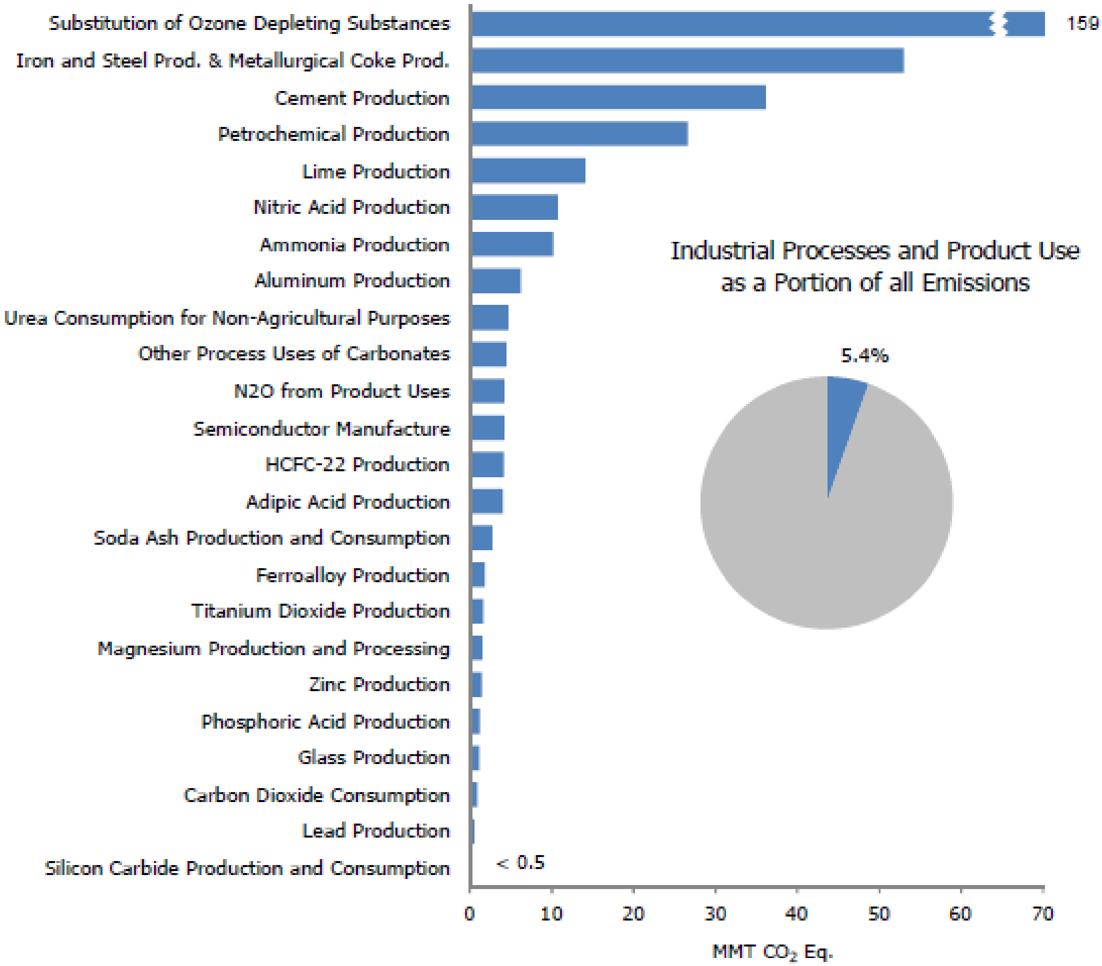
[147] Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

Figure 4-1: 2013 Industrial Processes and Product Use Chapter Greenhouse Gas Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources. 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 production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Emissions from mineral sources have either increased or not changed significantly since 1990 but largely track economic cycles, while CO_2 and CH_4 emissions from chemical sources have either decreased or not changed significantly. HFC emissions from the substitution of ozone depleting substances have increased drastically since 1990, while the emission trends of HFCs, PFCs, SF_6, and NF_3 from other sources are mixed. N_2O emissions from the production of adipic and nitric acid have decreased, while N_2O emissions from product uses has remained nearly constant over time. Trends are explained further within each emission source category throughout the chapter.

Table 4-1 summarizes emissions for the IPPU chapter in MMT CO_2 Eq. using *IPCC Fourth Assessment Report* (AR4) GWP values, following the requirements of the revised UNFCCC reporting guidelines for national inventories (IPCC 2007).[148] Unweighted native 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

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[148] See < http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf >.

reporting format tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**207.2**	**191.1**	**141.1**	**165.7**	**169.7**	**166.4**	**163.0**
Iron and Steel Production & Metallurgical Coke Production	99.8	66.7	43.0	55.7	60.0	54.3	52.3
Iron and Steel Production	*97.3*	*64.6*	*42.1*	*53.7*	*58.6*	*53.8*	*50.5*
Metallurgical Coke Production	*2.5*	*2.0*	*1.0*	*2.1*	*1.4*	*0.5*	*1.8*
Cement Production	33.3	45.9	29.4	31.3	32.0	35.1	36.1
Petrochemical Production	21.6	28.1	23.7	27.4	26.4	26.5	26.5
Lime Production	11.7	14.6	11.4	13.4	14.0	13.7	14.1
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.4	4.7	4.0	4.4	4.7
Other Process Uses of Carbonates	4.9	6.3	7.6	9.6	9.3	8.0	4.4
Aluminum Production	6.8	4.1	3.0	2.7	3.3	3.4	3.3
Soda Ash Production and Consumption	2.7	2.9	2.5	2.6	2.6	2.7	2.7
Ferroalloy Production	2.2	1.4	1.5	1.7	1.7	1.9	1.8
Titanium Dioxide Production	1.2	1.8	1.6	1.8	1.7	1.5	1.6
Zinc Production	0.6	1.0	0.9	1.2	1.3	1.5	1.4
Phosphoric Acid Production	1.6	1.4	1.0	1.1	1.2	1.1	1.2
Glass Production	1.5	1.9	1.0	1.5	1.3	1.2	1.2
Carbon Dioxide Consumption	1.5	1.4	1.8	1.2	0.8	0.8	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.1	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
CH_4	**1.4**	**1.0**	**0.5**	**0.7**	**0.8**	**0.8**	**0.8**
Iron and Steel Production & Metallurgical Coke Production	1.1	0.9	0.4	0.6	0.7	0.7	0.7
Iron and Steel Production	*1.1*	*0.9*	*0.4*	*0.6*	*0.7*	*0.7*	*0.7*
Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	0.2	0.1	+	0.1	+	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
N_2O	**31.6**	**22.8**	**16.7**	**20.1**	**25.5**	**20.4**	**19.1**
Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Adipic Acid Production	15.2	7.1	2.7	4.2	10.2	5.5	4.0
Semiconductor Manufacturing	+	0.1	0.1	0.1	0.2	0.2	0.2
HFCs	**46.6**	**131.4**	**142.9**	**152.6**	**157.4**	**159.2**	**163.0**
Substitution of Ozone Depleting Substances[a]	0.3	111.1	136.0	144.4	148.4	153.5	158.6
HCFC-22 Production	46.1	20.0	6.8	8.0	8.8	5.5	4.1
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	0.0	0.0	+	+	+	+	0.1
PFCs	**24.3**	**6.6**	**3.9**	**4.4**	**6.9**	**6.0**	**5.8**
Aluminum Production	21.5	3.4	1.9	1.9	3.5	2.9	3.0
Semiconductor Manufacture	2.8	3.2	2.0	2.6	3.4	3.0	2.9
SF_6	**31.1**	**14.0**	**9.3**	**9.5**	**10.0**	**7.7**	**6.9**

Electrical Transmission and Distribution	25.4	10.6	7.3	7.0	6.8	5.7	5.1
Magnesium Production and Processing	5.2	2.7	1.6	2.1	2.8	1.6	1.4
Semiconductor Manufacture	0.5	0.7	0.3	0.4	0.4	0.4	0.4
NF_3	**+**	**0.5**	**0.4**	**0.5**	**0.7**	**0.6**	**0.6**
Semiconductor Manufacture	+	0.5	0.4	0.5	0.7	0.6	0.6
Total	**342.1**	**367.4**	**314.9**	**353.6**	**371.0**	**361.2**	**359.1**

Notes: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Small amounts of PFC emissions also result from this source.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CO_2	**207,166**	**191,101**	**141,126**	**165,737**	**169,727**	**166,359**	**162,979**
Iron and Steel Production & Metallurgical Coke Production	99,781	66,666	43,029	55,746	60,008	54,327	52,288
Iron and Steel Production	*97,311*	*64,623*	*42,073*	*53,662*	*58,583*	*53,786*	*50,466*
Metallurgical Coke Production	*2,470*	*2,043*	*956*	*2,084*	*1,425*	*542*	*1,822*
Cement Production	33,278	45,910	29,432	31,256	32,010	35,051	36,146
Petrochemical Production	21,633	28,124	23,706	27,388	26,396	26,477	26,514
Lime Production	11,700	14,552	11,411	13,381	13,981	13,715	14,072
Ammonia Production	13,047	9,196	8,454	9,188	9,292	9,377	10,152
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	3,427	4,730	4,029	4,449	4,663
Other Process Uses of Carbonates	4,907	6,339	7,583	9,560	9,335	8,022	4,424
Aluminum Production	6,831	4,142	3,009	2,722	3,292	3,439	3,255
Soda Ash Production and Consumption	2,741	2,868	2,488	2,612	2,624	2,672	2,712
Ferroalloy Production	2,152	1,392	1,469	1,663	1,735	1,903	1,785
Titanium Dioxide Production	1,195	1,755	1,648	1,769	1,729	1,528	1,608
Zinc Production	632	1,030	943	1,182	1,286	1,486	1,429
Phosphoric Acid Production	1,586	1,395	1,016	1,130	1,198	1,138	1,173
Glass Production	1,535	1,928	1,045	1,481	1,299	1,248	1,160
Carbon Dioxide Consumption	1,472	1,375	1,795	1,206	802	841	903
Lead Production	516	553	525	542	538	527	525
Silicon Carbide Production and Consumption	375	219	145	181	170	158	169
Magnesium Production and Processing	1	3	1	1	3	2	2
CH_4	**56**	**40**	**20**	**27**	**30**	**33**	**32**
Iron and Steel Production & Metallurgical Coke Production	46	34	17	25	28	29	28
Iron and Steel Production	*46*	*34*	*17*	*25*	*28*	*29*	*28*
Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	9	6	2	2	2	3	3
Ferroalloy Production	1	+	+	+	+	1	+
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
N_2O	**106**	**76**	**56**	**68**	**86**	**69**	**64**
Nitric Acid Production	41	38	32	39	37	35	36
N_2O from Product Uses	14	14	14	14	14	14	14
Adipic Acid Production	51	24	9	14	34	19	13
Semiconductor Manufacture	+	+	+	+	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**

Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	1	1	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Aluminum Production	M	M	M	M	M	M	M
Semiconductor Manufacture	M	M	M	M	M	M	M
SF_6	**2**	**1**	**+**	**+**	**1**	**+**	**+**
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+
NF_3	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Semiconductor Manufacture	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt

M (Mixture of gases)

Note: Totals may not sum due to independent rounding.

[a] Small amounts of PFC emissions also result from this source.

The UNFCCC incorporated the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* as the standard for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This chapter presents emission estimates calculated in accordance with the methodological guidance provided in these guidelines.

QA/QC and Verification Procedures

For industrial processes and product use sources, a detailed QA/QC plan was developed and implemented. This plan was based on the overall U.S. QA/QC plan, but was tailored to include specific procedures recommended for these sources. Two types of checks were performed using this plan: (1) general, or Tier 1, procedures 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, or Tier 2, procedures that focus on checks 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, where possible, consistent and reputable data sources are used across sources; that interpolation or extrapolation techniques are consistent across sources; and that common datasets and factors are used where applicable. Tier 1 quality assurance and quality control procedures have been performed for all industrial process and product use sources. Tier 2 procedures were performed for more significant emission categories, consistent with the IPCC *Good Practice Gudelines*.

For most industrial process and product use categories, activity data is obtained through a survey of manufacturers conducted by various organizations (specified within each source); the uncertainty of the activity data is a function of the reliability of reported plant-level production data and is influenced by the completeness of the survey response. The emission factors used are defaults from IPCC, derived using calculations that assume precise and efficient chemical reactions, or were based upon empirical data in published references. As a result, uncertainties in the emission coefficients can be attributed to, among other things, inefficiencies in the chemical reactions associated with each production process or to the use of empirically-derived emission factors that are biased; therefore, they may not represent U.S. national averages. Additional assumptions are described within each source.

The uncertainty analysis performed to quantify uncertainties associated with the 2013 emission estimates from industrial processes and product use continues a multi-year process for developing credible quantitative uncertainty estimates for these source categories using the IPCC Tier 2 approach. As the process continues, the type and the characteristics of the actual probability density functions underlying the input variables are identified and better characterized (resulting in development of more reliable inputs for the model, including accurate characterization of correlation between variables), based primarily on expert judgment. Accordingly, the quantitative uncertainty estimates reported in this section should be considered illustrative and as iterations of ongoing efforts to produce accurate uncertainty estimates. The correlation among data used for estimating emissions for different sources can influence the uncertainty analysis of each individual source. While the uncertainty analysis recognizes very significant connections among sources, a more comprehensive approach that accounts for all linkages will be identified as the uncertainty analysis moves forward.

Box 4-1: Industrial Processes Data from EPA's Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. EPA published a rule requiring annual of greenhouse gas data from large GHG 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). The rule 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 reported for facilities subject to 40 CFR part 98, though some source categories first reported data for calendar year 2011.

EPA's GHGRP dataset and the data presented in this Inventory report are complementary. EPA presents the data collected by EPA's GHGRP through a data publication tool (ghgdata.epa.gov) that allows data to be viewed in several formats, including maps, tables, charts, and graphs for individual facilities or groups of facilities. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. This may differ from the more aggregated data collected for the inventory to estimate total, national U.S. emissions. It should be noted that the definitions for source categories in the GHGRP may differ from those used in this Inventory in meeting the UNFCCC reporting guidelines (IPCC 2011). In line with the UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from source categories identified in the IPCC guidelines. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the EPA's GHGRP website.

For certain source categories in this Inventory (e.g., nitric acid production and petrochemical production), EPA has also integrated data values that have been calculated by aggregating GHGRP data that is 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 publishing only data values that meet these aggregation criteria.[149] Specific uses of aggregated facility-level data are described in the respective methodological sections. For other source categories in this chapter, as indicated in the respective planned improvements sections, 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.

4.1 Cement Production (IPCC Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of CO_2 from both the energy consumed in making the cement and the chemical process itself. Emissions from fuels consumed for energy purposes during the production of cement are accounted for in the Energy chapter.

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[149] U.S. EPA Greenhouse Gas Reporting Program, September 16, 2014 Developments on Publication of Aggregated Greenhouse Gas Data, see http://www.epa.gov/climate/ghgreporting/reporters/cbi/index.html

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of about 1,450°C (2,400°F) 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 cement production is directly proportional to the lime content of the clinker. During calcination, each mole of limestone ($CaCO_3$) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier byproduct CO_2 being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum and potentially other materials (e.g., slag), and used to make Portland cement.[150]

CO_2 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 35 states and Puerto Rico. Texas, Missouri, California, Pennsylvania, and Florida were the five leading cement-producing States in 2013 and accounted for approximately 48 percent of total U.S. production (USGS 2014). Clinker production in 2013 increased approximately 3 percent from 2012 levels. This increase can be attributed to an increase in spending in new residential construction and nonresidential buildings. In 2013, U.S. clinker production totaled 69,901 kilotons (USGS 2014). The resulting CO_2 emissions were estimated to be 36.1 MMT CO_2 Eq. (36,146 kt) (see Table 4-3).

Table 4-3: CO_2 Emissions from Cement Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	33.3	33,278
2005	45.9	45,910
2009	29.4	29,432
2010	31.3	31,256
2011	32.0	32,010
2012	35.1	35,051
2013	36.1	36,146

Greenhouse gas emissions from cement production increased every year from 1991 through 2006 (with the exception of a slight decrease in 1997), but decreased in the following years until 2009. Emissions from cement production were at their lowest levels in 2009 (2009 emissions are approximately 28 percent lower 2008 emissions and 12 percent lower than 1990). Since 2010, emissions have increased slightly. In 2013, emissions from cement production increased by 3 percent from the 2012 levels.

Emissions since 1990 have increased by 9 percent. Emissions decreased significantly between 2008 and 2009, due to the economic recession and associated decrease in demand for construction materials. Emissions increased slightly from 2009 levels in 2010, and increased slightly again in 2011, 2012, and in 2013 due to increasing consumption. 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 influence on cement production.

Methodology

CO_2 emissions were estimated using the Tier 2 methodology from the *2006 IPCC Guidelines*. 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, and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies

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[150] Approximately three percent of total clinker production is used to produce masonry cement, which is produced using plasticizers (e.g., ground limestone, lime) and Portland cement (USGS 2011). Carbon dioxide emissions that result from the production of lime used to create masonry cement are included in the Lime Manufacture source category.

the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime fraction for clinker of 65 percent and a constant reflecting the mass of CO_2 released per unit of lime. The 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 0.51 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$EF_{clinker} = 0.6460\ \mathrm{CaO} \times [(44.01\ \mathrm{g/mole}\ CO_2) \div (56.08\ \mathrm{g/mole\ CaO})] = 0.5070\ \mathrm{tons}\ CO_2/\mathrm{ton\ clinker}$$

During clinker production, some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO_2 emissions should be estimated as two percent of the CO_2 emissions calculated from clinker production (when data on CKD generation are not available). Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2006).

Furthermore, 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 magnesium oxide is not used, since the amount of magnesium oxide 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 (see Table 4-4) were obtained from USGS (Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014).The data were compiled by USGS (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including the facilities in Puerto Rico.

Table 4-4: Clinker Production (kt)

Year	Clinker
1990	64,355
2005	88,783
2009	56,918
2010	60,444
2011	61,903
2012	67,784
2013	69,901

Note: Clinker production from 1990-2013 includes Puerto Rico. Data were obtained from USGS (Van Oss 2013a; USGS 2014), whose original data source was USGS and U.S. Bureau of Mines Minerals Yearbooks (2013 data obtained from mineral industry surveys for cement in June 2014).

Uncertainty and Time-Series Consistency

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). CKD loss can range from 1.5 to 8 percent depending upon plant specifications. 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 surface area. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-5. 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, 2013 CO_2 emissions from cement production were estimated to be between 34.0 and 38.3 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 6 percent below and 6 percent above the emission estimate of 36.1 MMT CO_2 Eq.

Table 4-5: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	36.1	34.0	38.3	-6%	+6%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements involve evaluating and analyzing data reported under EPA’s GHGRP that would be useful to improve the emission estimates for the Cement Production source category. 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 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.[151]

4.2 Lime Production (IPCC Source Category 2A2)

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce 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 of the CO_2 generated during the production process, however, is recovered at some facilities for use in sugar refining and precipitated calcium carbonate (PCC) production.[152] Emissions from fuels consumed for energy purposes during the production of lime are accounted for in the Energy chapter.

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[151] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>

[152] PCC is obtained from the reaction of CO_2 with calcium hydroxide. It is used as a filler and/or coating in the paper, food, and plastic industries.

For U.S. operations, the term “lime” actually refers to a variety of chemical compounds. These include calcium oxide (CaO), or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ($[CaO\bullet MgO]$); and dolomitic hydrate ($[Ca(OH)_2\bullet MgO]$ or $[Ca(OH)_2\bullet Mg(OH)_2]$).

The contemporary lime market is approximately distributed across five end-use categories as follows: metallurgical uses, 38 percent; environmental uses, 31 percent; chemical and industrial uses, 22 percent; construction uses, 8 percent; and refractory dolomite, 1 percent. The major uses are in steel making, flue gas desulfurization systems at coal-fired electric power plants, construction, and water purification. 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.

Lime production in the United States—including Puerto Rico— was reported to be 19,210 kilotons in 2013 (Corathers 2014). Principal lime producing states are Alabama, Kentucky, Missouri, Nevada, Ohio, Pennsylvania, and Texas.

U.S. lime production resulted in estimated net CO_2 emissions of 14.1 MMT CO_2 Eq. (14,072 kt) (see Table 4-6 and Table 4-7). The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described below.

Table 4-6: CO_2 Emissions from Lime Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	11.7	11,700
2005	14.6	14,552
2009	11.4	11,411
2010	13.4	13,381
2011	14.0	13,981
2012	13.7	13,715
2013	14.1	14,072

Table 4-7: Potential, Recovered, and Net CO_2 Emissions from Lime Production (kt)

Year	Potential	Recovered[a]	Net Emissions
1990	11,959	259	11,700
2005	15,074	522	14,552
2009	11,872	461	11,411
2010	13,776	395	13,381
2011	14,389	407	13,981
2012	14,188	473	13,715
2013	14,539	467	14,072

[a] For sugar refining and PCC production.

Note: Totals may not sum due to independent rounding.

In 2013, lime production was nearly the same as 2011 levels (increase of 1 percent) at 19,210 kilotons. In 2013, lime production increased from 2012 levels by approximately 3 percent. Lime production in 2010 rebounded from a 21 percent decline in 2009 to 18,219 kilotons, which is still 8 percent below 2008 levels. Lime production declined in 2009 mostly due to the economic recession and the associated significant downturn in major markets such as construction and steel. The surprising rebound in 2010 is primarily due to increased consumption in steelmaking, chemical and industrial uses, and in flue gas desulfurization.

Methodology

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors using the Tier 2 approach from the *2006 IPCC Guidelines* (IPCC 2006). 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:

For high-calcium lime:

$$[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole } CaO)] \times (0.9500 \text{ CaO/lime}) = 0.7455 \text{ g } CO_2\text{/g lime}$$

For dolomitic lime:

$$[(88.02 \text{ g/mole } CO_2) \div (96.39 \text{ g/mole } CaO)] \times (0.9500 \text{ CaO/lime}) = 0.8675 \text{ g } CO_2\text{/g lime}$$

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 [$Ca(OH)_2$•$Mg(OH)_2$]) (IPCC 2006). These factors set the chemically combined water content to 24.3 percent for high-calcium hydrated lime, and 27.2 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD). LKD is a byproduct of the lime manufacturing process. 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. Currently, data on annual LKD production is not readily available. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006).

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 2014) based on reported facility level data. The amount of CO_2 captured/recovered for on-site process use is deducted from the total potential emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-6 and Table 4-7. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2013. 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 (*2006 IPCC Guidelines*, Volume 1, Chapter 5). The prior estimates for CO_2 removal for 1990 through 2009 were adjusted based on the "overlap" technique recommended by IPCC. Refer to the Recalculations Discussion section, below, for more details.

Lime production data (by type, high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2013 (see Table 4-8) were obtained from USGS (1992 through 2013, Corathers 2014) and are compiled by USGS to the nearest ton. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2011). 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 is presented in Table 4-9 (IPCC 2006). The CaO and CaO•MgO contents of lime were obtained from the IPCC (IPCC 2006). Since data for the individual lime types (high calcium and dolomitic) were not provided prior to 1997, total lime production for 1990 through 1996 was calculated according to the three year distribution from 1997 to 1999.

Table 4-8: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	High-Calcium Quicklime	Dolomitic Quicklime	High-Calcium Hydrated	Dolomitic Hydrated	Dead-Burned Dolomite
1990	11,166	2,234	1,781	319	342
2005	14,100	2,990	2,220	474	200
2009	11,800	1,830	1,690	261	200
2010	13,300	2,570	1,910	239	200

Year	High-Calcium Quicklime	Dolomitic Quicklime	High-Calcium Hydrated	Dolomitic Hydrated	Dead-Burned Dolomite
2011	13,900	2,690	2,010	230	200
2012	13,600	2,710	2,020	237	200
2013	13,800	2,870	2,050	260	230

Table 4-9: Adjusted Lime Production (kt)

Year	High-Calcium	Dolomitic
1990	12,466	2,800
2005	15,721	3,522
2009	13,034	2,213
2010	14,694	2,937
2011	15,367	3,051
2012	15,075	3,076
2013	15,297	3,282

Note: Minus water content of hydrated lime

Uncertainty and Time Series Consistency

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" are required to quantify the amount of CO_2 that is reabsorbed. Research conducted thus far has not yielded the necessary information to quantify CO_2 reabsorption rates.[153] However, some additional information on the amount of CO_2 consumed on site at lime facilities has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[154] 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 C is present from the wood. Kraft mills

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[153] 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).

[154] 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 [$Ca(OH)_2 + heat \rightarrow CaO + H_2O$] and no CO_2 is released.

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 (C) fluxes from changes in biogenic C 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. The National Lime association 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 (~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). There is limited data publicly available on LKD generation rates and also quantities, types of other byproducts/wastes produced at lime facilities. Further research and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on the IPCC Guidelines.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-10. Lime CO_2 emissions for 2013 were estimated to be between 13.7 and 14.4 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 3 percent below and 3 percent above the emission estimate of 14.1 MMT CO_2 Eq.

Table 4-10: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	14.1	13.7	14.4	-3%	+3%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Updated CO_2 recovery data was used for this category, aggregating reported facility level data from the GHGRP data on amount of CO_2 captured for on-site process use 2010 through 2013 (EPA 2014). Since these data were not available for the entire time series, IPCC-recommended "splicing" techniques were followed to estimate CO_2 removals for 1990 through 2009. In cases where the same method and data source is not available for the entire time series, IPCC recommends the use of "splicing" techniques to maintain time series consistency.

Of these, overlap is the only suitable method that could be applied to revise the 1990 through 2009 CO_2 removal estimates. The surrogate data method is not applicable due to absence of appropriate surrogate data for CO_2 removal. Interpolation and trend extrapolation methods are not suitable for longer time-periods (1990 through 2009). Therefore, the overlap method was selected to revise the prior 1990 through 2009 removal estimates.

According to the IPCC overlap method (IPCC 2006), the prior CO_2 removal estimates for 1990 through 2009 were multiplied by an adjustment factor. The adjustment factor is the average ratio of the removal estimates prepared using the new and the method previously used during the period of overlap (2010 through 2013).

$$y_0 = x_0 \times \left(\frac{1}{(n - m + 1)} \times \sum_{i=m}^{n} \frac{y_i}{x_i} \right)$$

where:

y_0 = the recalculated emission or removal estimate computed using overlap method
x_0 = the estimate developed using the previously used method
y_i = estimate(s) prepared using the new method during the period of overlap (2010-2013)
x_i = estimate(s) prepared using the previously-used method during the period of overlap (2010-2013)
m = starting year for the period of overlap (2010)
n = ending year for the period of overlap (2013)

Using the above equation, the adjustment factor was calculated to be 0.4815. The prior removal estimates for 1990 through 2009 were multiplied by this adjustment factor to obtain the revised removal estimates. This change resulted in a decrease of the annual CO_2 removal estimates by approximately half. As a result of the decreased removal estimates, the net CO_2 emissions from lime production increase for the entire time series. In the previous Inventory reports, the CO_2 removal estimates (i.e., CO_2 captured/recovered) were calculated using lime consumption data for PCC production and sugar refining. PCC producers and sugar refineries recover CO_2 emitted by lime production facilities for use as an input into production or refining processes. For CO_2 recovery by sugar refineries, lime consumption estimates (Corathers 2014) were multiplied by a CO_2 recovery factor to determine the total amount of CO_2 recovered from lime production facilities. According to industry outreach by state agencies and USGS, sugar refineries use captured CO_2 for 100 percent of their CO_2 input (Lutter 2009, Miller 2013). Carbon dioxide recovery by PCC producers was determined by multiplying lime consumption for PCC production (USGS 1992 through 2013, Corathers 2014) with the percentage CO_2 of production weight for PCC production at lime plants (i.e., $CO_2/CaCO_3 = 44/100$) and a CO_2 recovery factor based on the amount of purchased CO_2 by PCC manufacturers (Prillaman 2008 through 2012, Miller 2013). As data were only available starting in 2007, CO_2 recovery for the period 1990 through 2006 was extrapolated by determining a ratio of PCC production at lime facilities to lime consumption for PCC (USGS 1992 through 2008).

Planned Improvements

Future improvements involve continuing research to improve current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty and Time Series Consistency section per comments from the National Lime Association. Pending resources and data availability, historical CO_2 recovery rates at U.S. facilities producing lime will be investigated to further evaluate results from use of overlap method to improve time series consistency.

4.3 Glass Production (IPCC Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of CO_2 from both the energy consumed in making glass and the glass process itself. Emissions from fuels consumed for energy purposes during the production of glass are accounted for in the Energy sector.

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) which 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 are used to make glass more chemically stable and to 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) (OIT 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the process or other glass spillage or retention such as recycling or cullet broker services.

The raw materials (primarily limestone, dolomite and soda ash) 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 Carbonates Use (i.e., limestone/dolomite use), but has the same net effect in terms of 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 over 1,500 companies that manufacture glass in the United States, with the largest being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[155]

In 2013, 335 kilotons of limestone and 2,440 kilotons of soda ash were consumed for glass production in 2013 (USGS 2014b, Willett 2014). Dolomite consumption data for glass manufacturing was not publicly available for 2013. Use of limestone and soda ash in glass production resulted in aggregate CO_2 emissions of 1.2 MMT CO_2 Eq. (1,160 kt) (see Table 4-11). Overall, emissions have decreased 24 percent from 1990 through 2013.

Emissions from glass production 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. 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 a corresponding decrease in emissions. Furthermore, the glass container sector is one of the leading soda ash consuming sectors in the United States. Some commercial food and beverage package 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 2013b).

Table 4-11: CO_2 Emissions from Glass Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,535
2005	1.9	1,928
2009	1.0	1,045
2010	1.5	1,481
2011	1.3	1,299
2012	1.2	1,248
2013	1.2	1,160

Methodology

CO_2 emissions were calculated based on the *IPCC 2006 Guidelines* Tier 3 method by multiplying the quantity of input carbonates (limestone, dolomite, and soda ash) by the carbonate-based emission factor (in metric tons CO_2/metric ton carbonate): limestone, 0.43971; dolomite, 0.47732; and soda ash, 0.41492.

Consumption data for 1990 through 2013 of limestone, dolomite, and soda ash used for glass manufacturing were obtained from the USGS *Minerals Yearbook: Crushed Stone Annual Report* (1995 through 2014), 2013 preliminary data from the USGS Crushed Stone Commodity Expert (Willett 2014), the *USGS Minerals Yearbook: Soda Ash Annual Report* (1995 through 2013), USGS Mineral Industry Surveys for Soda Ash in August 2014 (USGS 2014)

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[155] 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>.

and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

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; or (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years.

There is a large quantity of limestone and dolomite reported to the USGS under the categories “unspecified–reported” and “unspecified–estimated.” A portion of this consumption is believed to be limestone or dolomite used for glass manufacturing. The quantities listed under the “unspecified” categories were, therefore, allocated to glass manufacturing according to the percent limestone or dolomite consumption for glass manufacturing end use for that year.[156]

Based on the 2013 reported data, the estimated distribution of soda ash consumption for glass production compared to total domestic soda ash consumption is 48 percent (USGS 2014b).

Table 4-12: Limestone, Dolomite, and Soda Ash Consumption Used in Glass Production (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
Limestone	430	920	139	999	614	555	335
Dolomite	59	541	0	0	0	0	0
Soda Ash	3,177	3,050	2,370	2,510	2,480	2,420	2,440
Total	**3,666**	**4,511**	**2,509**	**3,509**	**3,094**	**2,975**	**2,775**

Uncertainty and Time-Series Consistency

The uncertainty levels presented in this section arise in part due to variations in the chemical composition of limestone used in glass production. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals (potassium carbonate, strontium carbonate and barium carbonate, and dead burned dolomite). Similarly, the quality of the limestone (and mix of carbonates) used for glass manufacturing will depend on the type of glass being manufactured.

The estimates below also account for uncertainty associated with activity data. 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 manufacturer of the input carbonates (limestone, dolomite & soda ash) and not the end user. For 2013, there has been no reported consumption of dolomite for glass manufacturing. This data has been reported to USGS by dolomite manufacturers and not end-users (i.e., glass manufacturers). There is a high uncertainty associated with this estimate, as dolomite is a major raw material consumed in glass production. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. The uncertainty of the estimates for limestone and dolomite used in glass making is especially high; however, since glass making accounts for a small percent of consumption, its contribution to the overall emissions estimate is low. 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. Further research is needed into alternate and more complete sources of data on carbonate-based raw material consumption by the glass industry.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-13. In 2013, glass production CO_2 emissions were estimated to be between 1.1 and 1.2 MMT CO_2 Eq. at the 95 percent confidence

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[156] This approach was recommended by USGS.

level. This indicates a range of approximately 5 percent below and 5 percent above the emission estimate of 1.2 MMT CO_2 Eq.

Table 4-13: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	1.2	1.1	1.2	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Limestone consumption data for 2012 were revised to reflect updated USGS data. This change resulted in an insignificant increase of CO_2 emissions (less than 1 kt of CO_2). The preliminary data for 2012 was obtained directly from the USGS Crushed Stone Commodity Expert (Willett 2013). In June 2014, USGS published the 2012 Minerals Yearbook for Crushed Stone and the preliminary data was revised to reflect the latest USGS published data. The published time series was reviewed to ensure time series consistency. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Currently, only limestone and soda ash consumption data for glass manufacturing is publicly available. While limestone and soda ash are the predominant carbonates used in glass manufacturing, there are other carbonates that are also consumed for glass manufacturing, although in smaller quantities (e.g. dolomite). Pending resources, future improvements will include research into other sources of data for carbonate consumption by the glass industry.

Additionally, future improvements will also involve evaluating and analyzing data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Glass Production source category. 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. Further, EPA's GHGRP has an emission threshold for reporting, so the data do not account for all glass production in the United States. 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.[157]

4.4 Other Process Uses of Carbonates (IPCC Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$)[158], and other carbonates such as magnesium carbonate and iron carbonate are basic materials used by a wide variety of industries, including construction, agriculture, chemical,

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[157] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

[158] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

metallurgy, glass production, and environmental pollution control. This section addresses only limestone and dolomite use. For industrial applications, carbonates such as limestone and dolomite 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 other process sectors such as cement, lime, glass production, and iron and steel, are excluded from this section and reported under their respective source categories (e.g., glass manufacturing IPCC Source Category 2A7.) Emissions from fuels consumed for energy purposes during these processes are accounted for in the Energy chapter.

Limestone is 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. The leading limestone producing States are Texas, Missouri, Pennsylvania, Kentucky, and Ohio (USGS 2014). Similarly, dolomite deposits are also widespread throughout the world. Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Illinois, Pennsylvania, New York, Michigan, and Indiana (USGS 2013c).

In 2013, 10,010 kt of limestone and 1,212 kt of dolomite were consumed for these emissive applications, excluding glass manufacturing (Willett 2014). Usage of limestone and dolomite resulted in aggregate CO_2 emissions of 4.4 MMT CO_2 Eq. (4,424 kt) (see Table 4-14 and Table 4-15). Overall, emissions have decreased 10 percent from 1990 through 2013.

Table 4-14: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	Flux Stone	FGD	Magnesium Production	Other Miscellaneous Uses	Total
1990	2.6	1.4	0.1	0.8	4.9
2005	2.6	3.0	+	0.7	6.3
2009	1.8	5.4	+	0.4	7.6
2010	1.6	7.1	+	0.9	9.6
2011	1.5	5.4	+	2.4	9.3
2012	1.1	5.8	+	1.1	8.0
2013	0.9	3.0	+	0.5	4.4

Notes: Totals may not sum due to independent rounding. "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

+ Emissions are less than 0.05 MMT CO_2 Eq.

Table 4-15: CO_2 Emissions from Other Process Uses of Carbonates (kt)

Year	Flux Stone	FGD	Magnesium Production	Other Miscellaneous Uses	Total
1990	2,592	1,432	64	819	4,907
2005	2,649	2,973	+	718	6,339
2009	1,784	5,403	+	396	7,583
2010	1,560	7,064	+	937	9,560
2011	1,467	5,420	+	2,449	9,335
2012	1,077	5,797	+	1,148	8,022
2013	947	3,002	+	474	4,424

+ Emissions are less than 0.5 kt

Methodology

CO_2 emissions were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively, Table 2.1–limestone: 0.43971 tonne CO_2/tonne carbonate, and dolomite: 0.47732 tonne CO_2/tonne carbonate.[159] This methodology was used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining. Flux stone used during the production of iron and steel was deducted from the Other Process Uses of Carbonates estimate and attributed to the Iron and Steel Production estimate. Similarly limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Historically, the production of magnesium metal was the only other significant use of limestone and dolomite that produced CO_2 emissions. 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 1995 through 2012b; USGS 2013a).

Consumption data for 1990 through 2013 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining (see Table 4-16) were obtained from the USGS *Minerals Yearbook: Crushed Stone Annual Report* (1995 through 2014), preliminary data for 2013 from USGS Crushed Stone Commodity Expert (Willett, 2014), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. The production capacity data for 1990 through 2013 of dolomitic magnesium metal also came from the USGS (1995 through 2012, USGS 2013a) and the U.S. Bureau of Mines (1990 through 1993b). During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

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.

There is a large quantity of crushed stone 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 each reported end-use according to each end-use’s fraction of total consumption in that year.[160]

Table 4-16: Limestone and Dolomite Consumption (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
Flux Stone	6,737	7,022	4,623	4,440	4,396	3,666	3,317
Limestone	5,804	3,165	1,631	1,921	2,531	3,108	2,119
Dolomite	933	3,857	2,992	2,520	1,865	559	1,199
FGD	3,258	6,761	12,288	16,064	12,326	13,185	6,827
Other Miscellaneous Uses	1,835	1,632	898	2,121	5,548	2,610	1,078
Total	**11,830**	**15,415**	**17,809**	**22,626**	**22,270**	**19,461**	**11,222**

Uncertainty and Time-Series Consistency

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

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[159] *IPCC 2006 Guidelines*, Volume 3: Chapter 2

[160] This approach was recommended by USGS, the data collection agency.

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/industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, 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.

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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-17. Other Process Uses of Carbonates CO_2 emissions in 2013 were estimated to be between 4.1 and 4.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 4.4 MMT CO_2 Eq.

Table 4-17: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Other Process Uses of Carbonates	CO_2	4.4	4.1	4.8	-8%	+8%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

4.5 Ammonia Production (IPCC Source Category 2B1)

Emissions of CO_2 occur during the production of synthetic ammonia, 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. Emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter.

In the United States, the majority of ammonia is produced using a natural gas feedstock; however 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. There are approximately 13 companies operating 25 ammonia producing facilities in 16 states. More than 57 percent of domestic ammonia production capacity is concentrated in the States of Louisiana (30 percent), Oklahoma (21 percent), and Texas (6 percent) (USGS 2014). The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions.

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts CH_4 to CO_2, carbon monoxide (CO), and 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. 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 in the shift conversion step. Carbon dioxide is removed from the process gas by the shift conversion process, and the hydrogen gas 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 are 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 the Cropland Remaining Cropland section of the *Land Use, Land-Use Change, and Forestry* chapter. 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 the Urea Consumption for Non-Agricultural Purposes section of this chapter.

Total emissions of CO_2 from ammonia production in 2013 were 10.2 MMT CO_2 Eq. (10,152 kt), and are summarized in Table 4-18 and Table 4-19. 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 22 percent. Emissions in 2013 have increased by approximately 8 percent from the 2012 levels.

Table 4-18: CO_2 Emissions from Ammonia Production (MMT CO_2 Eq.)

Source	1990	2005	2009	2010	2011	2012	2013
Ammonia Production	13.0	9.2	8.5	9.2	9.3	9.4	10.2
Total	**13.0**	**9.2**	**8.5**	**9.2**	**9.3**	**9.4**	**10.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values

Table 4-19: CO_2 Emissions from Ammonia Production (kt)

Source	1990	2005	2009	2010	2011	2012	2013
Ammonia Production	13,047	9,196	8,454	9,188	9,292	9,377	10,152
Total	**13,047**	**9,196**	**8,454**	**9,188**	**9,292**	**9,377**	**10,152**

Methodology

CO_2 emissions from production of synthetic ammonia from natural gas feedstock is based on the *2006 IPCC Guidelines* (IPCC 2006) Tier 1 and 2 method. A country-specific emission factor is developed and applied to national ammonia production to estimate emissions. The method uses a CO_2 emission factor published by the European Fertilizer Manufacturers Association (EFMA) that is based on natural gas-based ammonia production technologies that are similar to those employed in the United States. The CO_2 emission factor of 1.2 metric tons CO_2/metric ton NH_3 (EFMA 2000a) is applied to the percent of total annual domestic ammonia production from natural gas feedstock.

Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced 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 multiplied by total annual domestic urea production. This corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of NH_3 and CO_2 to urea (IPCC 2006, EFMA 2000b).

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 one plant located in Kansas. Annual ammonia and urea production are shown in Table 4-20. The CO_2 emission factor for production of ammonia from petroleum coke is based on plant specific data, wherein all carbon contained in the petroleum coke feedstock that is not used for urea production is assumed to be emitted to the atmosphere as CO_2 (Bark 2004). Ammonia and urea are assumed to be manufactured in the same manufacturing complex, as both the raw materials needed for urea production are produced by the ammonia production process. The CO_2 emission factor of 3.57 metric tons CO_2/metric ton NH_3 for the petroleum coke feedstock process (Bark 2004) is applied to the percent of total annual domestic ammonia production from petroleum coke feedstock.

The emission factor of 1.2 metric ton CO_2/metric ton NH_3 for production of ammonia from natural gas feedstock was taken from the EFMA Best Available Techniques publication, Production of Ammonia (EFMA 2000a). The EFMA reported an emission factor range of 1.15 to 1.30 metric ton CO_2/metric ton NH_3, with 1.2 metric ton CO_2/metric ton NH_3 as a typical value (EFMA 2000a). Technologies (e.g., catalytic reforming process, etc.) associated with this factor are found to closely resemble those employed in the United States for use of natural gas as a feedstock. The EFMA reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2. The emission factor of 3.57 metric ton CO_2/metric ton NH_3 for production of ammonia from petroleum coke feedstock was developed from plant-specific ammonia production data and petroleum coke feedstock utilization data for the ammonia plant located in Kansas (Bark 2004). As noted earlier, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. The total ammonia production data for 2011, 2012, and 2013 were obtained from American Chemistry Council (2014). For years before 2011, ammonia production data (See Table 4-20) was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2010) as reported in Current Industrial Reports Fertilizer Materials and Related Products annual and quarterly reports. Urea-ammonia nitrate production from petroleum coke for years through 2011 was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012), and from CVR Energy, Inc. Annual Report (CVR 2012 and 2014) for 2012 and 2013. Urea production data for 1990 through 2008 were obtained from the Minerals Yearbook: Nitrogen (USGS 1994 through 2009). Urea production data for 2009 through 2010 were obtained from the U.S. Bureau of the Census (U.S. Bureau of the Census 2010 and 2011). The U.S. Bureau of the Census ceased collection of urea production statistics, and urea production data for 2011and 2012 were obtained from the Minerals Yearbook: Nitrogen (USGS 2014). The urea production data for 2013 are not yet published and so 2012 data has been used as proxy for 2013.

Table 4-20: Ammonia Production and Urea Production (kt)

Year	Ammonia Production	Urea Production
1990	15,425	7,450
2005	10,143	5,270
2009	9,372	5,084
2010	10,084	5,122
2011	10,325	5,430
2012	10,305	5,220
2013	10,930	5,220

Uncertainty and Time-Series Consistency

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. 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 collocated plants from the same natural gas raw material.

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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-21. Ammonia Production CO_2 emissions were estimated to be between 9.4 and 10.9 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 10.2 MMT CO_2 Eq.

Table 4-21: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	10.2	9.4	10.9	-8%	+8%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Production estimates for urea production for the years 2011 and 2012 were updated using information obtained from the Minerals yearbook: Nitrogen (USGS 2014). This update resulted in an increase of emissions by approximately 3.5 percent in 2011 and 0.3 percent in 2012 emissions relative to the previous report.

Planned Improvements

Future improvements involve continuing to evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for the Ammonia Production source category. 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, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[161] Specifically, the planned improvements include assessing data to update the emission factors to include both fuel and feedstock CO_2 emissions and incorporate CO_2 capture and storage. Methodologies will also be updated if additional ammonia-production plants are found to use hydrocarbons other than natural gas for ammonia production.

4.6 Urea Consumption for Non-Agricultural Purposes

Urea is produced using ammonia and 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 are approximately 20 of these facilities operating in the United States.

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. CO_2 emissions associated with urea consumed for fertilizer are accounted for in the Cropland Remaining Cropland section of the *Land Use, Land-Use Change, and Forestry* chapter.

Urea is used as a nitrogenous fertilizer for agricultural applications and also in a variety of industrial applications. Urea's industrial applications 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 N_2O emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2013 were estimated to be 4.7 MMT CO_2 Eq. (4,663 kt), and are summarized in Table 4-22 and Table 4-23. Net CO_2 emissions from urea consumption for non-agricultural purposes in 2013 have increased by approximately 23 percent from 1990.

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[161] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

Table 4-22: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990	2005	2009	2010	2011	2012	2013
Urea Consumption	3.8	3.7	3. 4	4.7	4.0	4.4	4.7
Total	**3.8**	**3.7**	**3.4**	**4.7**	**4.0**	**4.4**	**4.7**

Table 4-23: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt)

Source	1990	2005	2009	2010	2011	2012	2013
Urea Consumption	3,784	3,653	3,427	4,730	4,029	4,449	4,663
Total	**3,784**	**3,653**	**3,427**	**4,730**	**4,029**	**4,449**	**4,663**

Methodology

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated by multiplying the amount of urea consumed in the United States for non-agricultural purposes 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, and consistent with the *2006 IPCC Guidelines* (IPCC 2006).

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 *Land Use, Land-Use Change, and Forestry* chapter (see Table 6-26) and is reported in Table 4-24, from the total domestic supply of urea. The domestic supply of urea is estimated based on the amount of urea produced plus the sum of net urea imports and exports. A factor of 0.73 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 producing urea from ammonia and CO_2. This corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of NH_3 and CO_2 to urea (IPCC 2006, EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the Minerals Yearbook: Nitrogen (USGS 1994 through 2009). Urea production data for 2009 through 2010 were obtained from the U.S. Bureau of the Census (2011). The U.S. Bureau of the Census ceased collection of urea production statistics in 2011, therefore, urea production data for 2011and 2012 were obtained from the Minerals Yearbook: Nitrogen (USGS 2014). Urea production data for 2013 are not yet publicly available and so 2012 data has been used as proxy. Urea import data for 2011 and 2012 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 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 (1998 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 4-24). 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). Urea exports and imports data for 2013 is not yet available and so 2012 data has been used as proxy.

Table 4-24: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	Urea Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports
1990	7,450	3,296	1,860	854
2005	5,270	4,779	5,026	536
2009	5,084	4,848	4,727	289
2010	5,122	5,152	6,631	152
2011	5,430	5,589	5,860	207
2012	5,220	5,762	6,944	336
2013	5,220	5,469	6,944	336

Uncertainty and Time-Series Consistency

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. 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 4-25. CO_2 emissions associated with urea consumption for non-agricultural purposes were estimated to be between 4.2 and 5.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below and 10 percent above the emission estimate of 4.7 MMT CO_2 Eq.

Table 4-25: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	4.7	4.2	5.1	-10%	+10%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Production estimates for urea production for the years 2011 and 2012 were updated using information obtained from the Minerals Yearbook: Nitrogen (USGS 2014). Also, the amount of urea consumed for agricultural purposes in the United States for 2012 was revised based on the most recent data obtained from the *Land Use, Land-Use Change, and Forestry* chapter (see Table 6-26). These updates resulted in an increase of emissions by approximately 1 percent in 2011 and a decrease of approximately 15 percent in 2012 emissions.

4.7 Nitric Acid Production (IPCC 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. It is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. Virtually all of the nitric acid produced in the United States is manufactured by the catalytic oxidation of ammonia (EPA 1997). There are two different nitric acid production methods: weak nitric acid and high-strength nitric acid. The first method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength acid (90 percent or greater nitric acid) can be produced from dehydrating, bleaching, condensing, and absorption of the weak nitric acid. The basic process technology for producing nitric acid has not changed significantly over time. Most U.S. plants were built between 1960 and 2000. As of 2013, there are 35 active weak nitric acid production plants and one high-strength nitric acid production plant in U.S. (EPA 2010b; EPA 2014).

During this reaction, N_2O is formed as a byproduct and is released from reactor vents into the atmosphere. Emissions from fuels consumed for energy purposes during the production of nitric acid are accounted for in the Energy chapter.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2O$$

Currently, the nitric acid industry controls emissions of NO and NO_2 (i.e., NO_x). As such, the industry in the United States uses 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. However, NSCR units are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. NSCR systems were installed in nitric plants built between 1971 and 1977, approximately one-third of the weak acid production plants have NSCRs. U.S. facilities are using both tertiary (e.g., NSCR) and secondary controls (alternate catalysts).

N_2O emissions from this source were estimated to be 10.7 MMT CO_2 Eq. (36 kt of N_2O) in 2013 (see Table 4-26). Emissions from nitric acid production have decreased by 12 percent since 1990, with the trend in the time series closely tracking the changes in production. Emissions have decreased by 26 percent since 1997, the highest year of production in the time series.

Table 4-26: N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	12.1	41
2005	11.3	38
2009	9.6	32
2010	11.5	39
2011	10.9	37
2012	10.5	35
2013	10.7	36

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Methodology

Emissions of N_2O were calculated using the estimation methods provided by the *2006 IPCC Guidelines* (IPCC 2006) and country specific methods from N_2O EPA's Greenhouse Gas Reporting Program. The *2006 IPCC*

Guidelines Tier 2 method was used to estimate emissions from nitric acid production for 1990 through 2009, and a country specific approach similar to the IPCC Tier 3 method was used to estimate N_2O emissions for 2010 through 2013.

2010 through 2013

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2013 by aggregating reported facility-level data (EPA 2014). In the United States, all nitric acid facilities producing weak nitric acid (30-70 percent in strength) are required to report annual GHG emissions data to EPA as per the requirements of its Greenhouse Gas Reporting Program (GHGRP). As of 2013, there are 35 facilities that report to EPA, including the known single high-strength nitric acid production facility in the United States (EPA 2014). All nitric acid (weak acid) facilities are required to calculate process emissions using a site-specific emission factor developed through annual performance testing under typical operating conditions or by directly measuring N_2O emissions using monitoring equipment. The high-strength nitric acid facility also reports N_2O emissions associated with weak acid production and this may capture all relevant emissions, pending additional further EPA research. More details on the calculation and monitoring methods applicable to Nitric Acid facilities can be found under Subpart V: Nitric Acid Production of the regulation, Part 98.[162]

1990 through 2009

Using the GHGRP data for 2010,[163] country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors). These emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the GHGRP data (i.e., 1990 through 2009): 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.98 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Based on the available data, it was assumed that emission factors for 2010 would be more representative of abatement application in 1990 through 2009. Initial review of historical data indicates that percent production with and without abatement change over time and also year over year due to changes in application of facility-level abatement technologies, maintenance of abatement technologies, and also due to plant closures and start-ups (EPA 2010a, 2012, 2013b; Desai 2012; CAR 2013). The installation dates of N_2O abatement technologies are not known at most facilities, but it is assumed that facilities reporting abatement technology use have had this technology installed and operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific N_2O emission factors were used in conjunction with annual production and national share of production with and without abatement technologies to estimate N_2O emissions for 1990 through 2009, using the following equation:

$$E_i = \left[\left(P_i \times \%P_{C,i} \times EF_c\right) + \left(P_i \times \%P_{unc,i} \times EF_{unc}\right)\right]$$

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)
$\%P_{c,i}$ = 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

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[162] Located at <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[163] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology was aggregated from the GHGRP facility-level data for 2010-2013 (i.e., percent production with and without abatement).

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 through 2010) (see Table 4-27). Publicly-available information on plant-level abatement technologies was used to estimate the shares of nitric acid production with and without abatement for 2008 and 2009 (EPA 2010a, 2012, 2013b; Desai 2012; CAR 2013). Publicly-available data on use of abatement technologies were not available for 1990-2007. Therefore, the share of national production with and without abatement for 2008 was assumed to be constant for 1990 through 2007.

Table 4-27: Nitric Acid Production (kt)

Year	kt
1990	7,195
2005	6,711
2009	5,924
2010	7,444
2011	7,606
2012	7,453
2013	7,572

Uncertainty and Time-Series Consistency

Uncertainty associated with the parameters used to estimate N_2O emissions includes that of production data, the share of U.S. nitric acid production attributable to each emission abatement technology 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, high pressure, etc.), and abatement technology type, installation date of abatement technology, and accurate destruction and removal efficiency rates.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-28. N_2O emissions from nitric acid production were estimated were estimated to be between 10.1 and 11.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2013 emissions estimate of 10.7 MMT CO_2 Eq.

Table 4-28: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	10.7	10.1	11.3	-5%	+5%

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

In addition, GHGRP data from subpart V of regulation 40 CFR Part 98 were used to recalculate emissions from nitric acid production over the entire time series (EPA 2014), and used directly for emission estimates for 2010 through 2013. Nitric acid production and N_2O emissions data were available for 2010 through 2013 from EPA's GHGRP, given nearly all nitric acid production facilities, with the exception of the strong acid facility, in the United States are required to report annual data under subpart V. Country-specific N_2O emission factors were developed using the 2010 GHGRP emissions and production data for nitric acid production with abatement and without abatement. Due to differences in operational efficiencies and recent installation of abatement technology at some U.S. facilities, 2010 GHGRP production data were used for recalculating time series emissions (1990 through 2009) instead of average factors developed from 2010 through 2013 GHGRP data. As per the 2010 GHGRP data, 70.7 percent of total domestic nitric acid production was estimated to be produced without any abatement.

Using the 2010 GHGRP data, emission factors for production with abatement and without abatement were calculated to be 3.3 kg N_2O/metric ton nitric acid produced and 5.98 kg N_2O/metric ton nitric acid produced, respectively. These emission factors and historical production data from the U.S. Census Bureau were used to calculate emissions for 1990 through 2009. The emission factors were used in conjunction with existing estimates on the share of production with and without N_2O abatement technology to estimate N_2O emissions for 1990 through 2009.

For 2009, an estimated 19.7 percent of nitric acid production was produced using N_2O abatement technology and 80.3 percent production was without abatement technology (EPA 2010a, 2013b, 2012; Desai 2012; CAR 2013). Similarly for 2008, an estimated 12.3 percent of nitric acid production was without abatement and 87.7 percent production was with abatement technology (EPA 2012). Since data on the use of abatement technology was not publicly available for 1990 through 2007, the national shares of production with and without abatement for 2008 were used for all prior years (i.e., 1990 through 2007).

Time series emissions for 1990 through 2009 were recalculated, and the revised emission estimates are approximately 30 percent lower than the prior estimates.

4.8 Adipic Acid Production (IPCC Source Category 2B3)

Adipic acid is produced through a two-stage process during which N_2O is generated in the second stage. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for in the Energy chapter. 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 adipic acid. N_2O 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:

$$\begin{aligned}(CH_2)_5CO(cyclohexanone) + \ (CH_2)_5CHOH(cyclohexanol) + \ wHNO_3 \\ \rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + \ xN_2O \ + yH_2O\end{aligned}$$

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). One small plant, which last operated in April 2006 and represented approximately two percent of production, did not control for N_2O (VA DEQ 2009; ICIS 2007; VA DEQ 2006). In 2013, catalytic reduction, non-selective catalytic reduction (NSCR) and thermal reduction abatement technologies were applied as N_2O abatement measures at adipic acid facilities (EPA 2014).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers. In 2013, the United States had two companies with a total of three adipic acid production facilities (two in Texas and one in Florida), all of which were operational (EPA 2014). The United States accounts for the largest share of global adipic acid production capacity (30 percent), followed by the European Union (29 percent) and China (22 percent) (SEI 2010). Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. Commercially, it 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).

N_2O emissions from adipic acid production were estimated to be 4.0 MMT CO_2 Eq. (13 kt) in 2013 (see Table 4-29). National adipic acid production has increased by approximately 11 percent over the period of 1990 through 2013, to approximately 840,000 metric tons (ACC 2014). Over the period 1990 to 2013, emissions have been reduced by 74 percent due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. In April 2006, the smallest of the four facilities ceased production of adipic acid (VA DEQ 2009); furthermore, one of the major adipic acid production facilities was not operational in 2009 or 2010 (Desai 2010). All three remaining facilities were in operation in 2013. Very little information on annual trends in the activity data exist for adipic acid.

Table 4-29: N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	15.2	51
2005	7.1	24
2009	2.7	9
2010	4.2	14
2011	10.2	34
2012	5.5	19
2013	4.0	13

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Methodology

Emissions are estimated using both Tier 2 and Tier 3 methods consistent with consistent the *2006 IPCC Guidelines* (IPCC 2006). Facility level greenhouse gas emissions data were obtained from the GHGRP for the years 2010 through 2013 (EPA 2014) and aggregated to national N_2O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to calculate emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or by directly measuring N_2O emissions using monitoring equipment. More information on the monitoring methods for process N_2O emissions applicable to adipic acid production facilities under Subpart E can be found in the electronic code of federal regulations.[164]

Due to confidential business information, plant names are not provided in this section. Therefore, the four adipic acid-producing facilities will be referred to as Plants 1 through 4. Plant 4 was closed in April 2006. Overall, as noted

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[164] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

above, the three plants that are currently operating facilities use abatement equipment. Plants 1 and 2 employ catalytic destruction and Plant 3 employs thermal destruction.

2010 through 2013

All emission estimates for 2010 through 2013 were obtained through analysis of the GHGRP data (EPA 2014), which is consistent with the *2006 IPCC Guidelines* (IPCC 2006) Tier 3 method.

1990 through 2009

For years prior to EPA's GHGRP reporting, for both Plants 1 and 2, 1990 to 2009 emission estimates were obtained directly from the plant engineer and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered confidential business information and hence are not published (Desai 2010). These estimates were based on continuous process monitoring equipment installed at the two facilities. In 2009 and 2010, no adipic acid production occurred at Plant 1 per reporting to EPA's GHGRP (EPA 2012; Desai 2011b).

For the Plant 4, 1990 through 2009 N_2O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines* until shutdown of the plant in 2006:

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

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, based on experiments that the reaction stoichiometry for N_2O production in the preparation of adipic acid at 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 abatement equipment operates during the annual production period. No abatement equipment was installed the Inolex/Allied Signal facility, which last operated in April 2006 (VA DEQ 2009). Plant-specific production data for this facility were obtained across the time series from 1990 through 2006 from the Virginia Department of Environmental Quality (VA DEQ 2010). 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 2011a). For 1990 through 2004, emissions were estimated using plant-specific production data and 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 2014; CMR 2001, 1998; CW 1999; C&EN 1995, 1994, 1993, and 1992). 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 and 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 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 kept the same as the 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 4-30) from 1990 through 2013 were obtained from the American Chemistry Council (ACC 2014).

Table 4-30: Adipic Acid Production (kt)

Year	kt
1990	755
2005	865
2009	650
2010	720
2011	810
2012	810
2013	840

Uncertainty and Time-Series Consistency

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, but also abatement technology destruction and removal efficiency rates and plant specific production levels.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-31. N_2O emissions from adipic acid production for 2013 were estimated to be between 3.8 and 4.2 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 2013 emission estimate of 4.0 MMT CO_2 Eq.

Table 4-31: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	4.0	3.8	4.2	-4%	+4%

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

4.9 Silicon Carbide Production and Consumption (IPCC Source Category 2B5)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used as an industrial abrasive. Silicon carbide is produced for abrasive, metallurgical, and other non-abrasive applications in the United States. Production for metallurgical and other non-abrasive applications is not available and therefore both CO_2 and CH_4 estimates are based solely upon production estimates of silicon carbide for abrasive applications. Emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the Energy chapter.

To produce SiC, silica sand or quartz (SiO_2) is reacted with carbon 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 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 is also emitted from the consumption of SiC for metallurgical and other non-abrasive applications.

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. The USGS reports that a portion (approximately 50 percent) of SiC is used in metallurgical and other non-abrasive applications, primarily in iron and steel production (USGS 2006a). 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. However, demand for SiC consumption in the United States has recovered somewhat from its lows in 2009 (USGS 2012a). Silicon carbide is manufactured at a single facility located in Illinois (USGS 2013b).

Carbon dioxide emissions from SiC production and consumption in 2013 were 0.17 MMT CO_2 Eq. (169 kt). Approximately 54 percent of these emissions resulted from SiC production while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2013 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4) (see Table 4-32: and Table 4-33). Emissions have fluctuated in recent years, but 2013 emissions are only about 45 percent of emissions in 1990.

Table 4-32: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990	2005	2009	2010	2011	2012	2013
CO_2	0.4	0.2	0.1	0.2	0.2	0.2	0.2
CH_4	+	+	+	+	+	+	+
Total	**0.4**	**0.2**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-33: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2009	2010	2011	2012	2013
CO_2	375	219	145	181	170	158	169
CH_4	1	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology

Emissions of CO_2 and CH_4 from the production of SiC were calculated using the Tier 1 method provided by the *2006 IPCC Guidelines* (IPCC 2006). Annual estimates of SiC production were multiplied by the appropriate emission factor, as shown below:

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1\ metric\ ton}{1000\ kg}\right)$$

where,

$E_{sc,CO2}$ = CO_2 emissions from production of SiC, metric tons
$E_{sc,CO2}$ = 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
$E_{sc,CH4}$ = Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines* (IPCC 2006):

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Emissions of CO_2 from silicon carbide consumption for metallurgical uses were calculated by multiplying the annual utilization of SiC for metallurgical uses (reported annually in the USGS Minerals Yearbook for Silicon) by the carbon content of SiC (31.5 percent), which was determined according to the molecular weight ratio of SiC.

Emissions of CO_2 from silicon carbide consumption for other non-abrasive uses were calculated by multiplying the annual SiC consumption for non-abrasive uses by the carbon content of SiC (31.5 percent). The annual SiC consumption for non-abrasive uses was calculated by multiplying the annual SiC consumption (production plus net imports) by the percent used in metallurgical and other non-abrasive uses (50 percent) (USGS 2006a) and then subtracting the SiC consumption for metallurgical use.

Production data for 1990 through 2012 were obtained from the Minerals Yearbook: Manufactured Abrasives (USGS 1991a through 2013a). Production data for 2013 were obtained from the Minerals Industry Surveys: Abrasives (Manufactured) (USGS 2014). Silicon carbide consumption by major end use was obtained from the Minerals Yearbook: Silicon (USGS 1991b through 2011b, 2012c, and 2013b) (see Table 4-34). Net imports for the entire time series were obtained from the U.S. Census Bureau (2005 through 2014).

Table 4-34: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,465
2005	35,000	220,149
2009	35,000	92,280
2010	35,000	154,540
2011	35,000	136,222
2012	35,000	114,265
2013	35,000	134,054

Uncertainty and Time-Series Consistency

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 would be 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). There is also uncertainty associated with the use or destruction of methane 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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-35. Silicon carbide production and consumption CO_2 emissions were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.17 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 9 percent below and 10 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-35: 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	2013 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	0.17	0.15	0.18	-9%	+9%
Silicon Carbide Production	CH_4	+	+	+	-9%	+10%

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

\+ Does not exceed 0.05 MMT CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter. This change caused a slight increase of emissions over the entire time series relative to the previous report.

Planned Improvements

Future improvements involve continuing to evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for the Silicon Carbide Production source category. Particular attention will be made to ensure time series consistency of the emission 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.[165] In addition, improvements will involve continued research to determine if calcium carbide production and consumption data are available for the United States. If these data are available, calcium carbide emission estimates will be included in this source category.

4.10 Titanium Dioxide Production (IPCC 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 CO_2. Emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for in the Energy chapter. The chloride process is based on the following chemical reactions:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2.

The 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 pigment in white paint, lacquers, and varnishes; it is also used as a pigment in the manufacture of paper, foods, plastics, and other products. In 2013, U.S. TiO_2 production totaled 1,200,000 metric tons (USGS 2014b). There were a total 6 plants producing TiO_2 in the United States—2 located in Mississippi, and single plants located in Delaware, Louisiana, Ohio, and Tennessee.

Emissions of CO_2 in 2013 were 1.6 MMT CO_2 Eq. (1,608 kt), which represents an increase of 35 percent since 1990 (see Table 4-36).

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[165] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

Table 4-36: CO_2 Emissions from Titanium Dioxide (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.2	1,195
2005	1.8	1,755
2009	1.6	1,648
2010	1.8	1,769
2011	1.7	1,729
2012	1.5	1,528
2013	1.6	1,608

Methodology

Emissions of CO_2 from TiO_2 production were calculated by multiplying annual national TiO_2 production by chloride-process-specific emission factors using a Tier 1 approach provided in *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation is as follows:

$$E_{td} = EF_{td} \times Q_{td}$$

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

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 post-2004 production uses the chloride process (USGS 2005). The percentage of production from the chloride process is estimated at 100 percent since 2004. 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* (IPCC 2006). Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2012 (see Table 4-37:) were obtained through the Minerals Yearbook: Titanium Annual Report (USGS 1991 through 2014a). Production data for 2013 was obtained from the Minerals Commodity Summary: Titanium and Titanium Dioxide (USGS 2014b). Data on the percentage of total TiO_2 production capacity that is 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 based on a discussion with Joseph Gambogi (2002). By 2002, only one sulfate plant remained online in the United States and this plant closed in 2004 (USGS 2005).

Table 4-37: Titanium Dioxide Production (kt)

Year	kt
1990	979
2005	1,310
2009	1,230
2010	1,320
2011	1,290
2012	1,140

2013	1,200

Uncertainty and Time-Series Consistency

Each year, 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 on the basis of prior year production levels and industry trends. Variability in response rates varies from 67 to 100 percent of TiO_2 pigment plants over the time series.

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 through the use of petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing 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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-38: Titanium dioxide consumption CO_2 emissions were estimated to be between 1.4 and 1.8 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 1.6 MMT CO_2 Eq.

Table 4-38: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	1.6	1.4	1.8	-13%	+13%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Production data for 2012 were updated relative to the previous Inventory based on recently published data in the USGS Minerals Yearbook: Titanium 2012 (USGS 2014a). This resulted in a 12 percent decrease in 2012 CO_2 emissions from TiO_2 production relative to the previous report.

Planned Improvements

Pending resources, a potential improvement to the Inventory estimates for this source category would include the derivation of country-specific emission factors, based on annual data reported under EPA's GHGRP for 2010 through 2013 (i.e. aggregated emissions and titanium production). Information on titanium dioxide production is collected by EPA's GHGRP for all facilities for years 2010 through 2013 and would also have to be assessed against criteria EPA has established to publish aggregated confidential business information (CBI) reported under EPA's GHGRP. In order to provide estimates for the entire time series (i.e., 1990 through 2009), the applicability of more recent GHGRP data to previous years' estimates will need to be evaluated, and additional data that could be utilized in the calculations for this source category may need to be researched. 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.[166]

In addition, the planned improvements include researching the significance of titanium-slag production in electric furnaces and synthetic-rutile production using the Becher process in the United States. Significant use of these production processes will be included in future estimates.

4.11 Soda Ash Production and Consumption (IPCC Source Category 2B7)

Carbon dioxide is generated as a byproduct of calcining trona ore to produce soda ash, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. Emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for in the Energy sector.

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:

$$2Na2CO_3 \bullet NaHCO_3 \bullet 2H_2O(Trona) \rightarrow 3Na2CO_3(Soda\ Ash) + 5H_2O + CO_2$$

Soda ash (sodium carbonate, Na_2CO_3) 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. (Emissions from soda ash used in glass production are reported under IPCC Source Category 2A7. Glass production is its own sub-category and historical soda ash consumption figures have been adjusted to reflect this change.) After glass manufacturing, soda ash is used primarily to manufacture many sodium-base inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2014). 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-fourth of total world soda ash output. Only two states produce natural soda ash: Wyoming and California. Of these two states, only net emissions of CO_2 from Wyoming were calculated due to specifics regarding the production processes employed in the state.[167] Based on preliminary 2013 reported data, the estimated distribution of soda ash by end-use in 2013 (excluding glass production) was chemical production, 54 percent; soap and detergent manufacturing, 14 percent; distributors, 11 percent; flue gas desulfurization, 8 percent; other uses, 8 percent; pulp and paper production, 3 percent; and water treatment, 2 percent (USGS 2014).

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[166] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

[167] 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 third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona 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 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.

U.S. natural soda ash is competitive in world markets because the majority of the world output of soda ash is made synthetically. Although the United States continues to be a major supplier of world soda ash, China, which surpassed the United States in soda ash production in 2003, is the world's leading producer. Despite this competition, U.S. soda ash exports are expected to increase, causing domestic production to increase slightly (USGS 2013).

In 2013, CO_2 emissions from the production of soda ash from trona were approximately 1.6 MMT CO_2 Eq. (1,610 kt). Soda ash consumption in the United States generated 1.1 MMT CO_2 Eq. (1,102 kt) in 2013. Total emissions from soda ash production and consumption in 2013 were 2.7 MMT CO_2 Eq. (2,712 kt) (see Table 4-39 and Table 4-40).

Total emissions in 2013 increased by approximately 1.5 percent from emissions in 2012, and have decreased overall by approximately 1.1 percent since 1990.

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 continued a trend of increased production and value in 2013 since experiencing a decline in domestic and export sales caused by adverse global economic conditions in 2009. The annual average unit value of soda ash set a record high in 2012, and soda ash exports increased as well, accounting for 55 percent of total production (USGS 2013).

Table 4-39: CO_2 Emissions from Soda Ash Production and Consumption Not Associated with Glass Manufacturing (MMT CO_2 Eq.)

Year	Production	Consumption	Total
1990	1.4	1.4	2.7
2005	1.6	1.3	2.9
2009	1.4	1.1	2.5
2010	1.5	1.1	2.6
2011	1.5	1.1	2.6
2012	1.6	1.1	2.7
2013	1.6	1.1	2.7

Note: Totals may not sum due to independent rounding.

Table 4-40: CO_2 Emissions from Soda Ash Production and Consumption Not Associated with Glass Manufacturing (kt)

Year	Production	Consumption	Total
1990	1,360	1,381	2,741
2005	1,573	1,296	2,868
2009	1,397	1,091	2,488
2010	1,471	1,141	2,612
2011	1,526	1,098	2,624
2012	1,582	1,090	2,672
2013	1,610	1,102	2,712

Note: Totals may not sum due to independent rounding.

Methodology

During the 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 can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2, or an emission factor of 0.097 metric tons CO_2 per metric ton trona (IPCC 2006). Thus, the 17.4 million metric tons of trona mined in 2013 for soda ash production (USGS 2014) resulted in CO_2 emissions of approximately 1.6 MMT CO_2 Eq. (1,610 kt).

Once produced, most soda ash is consumed in chemical and soap production, with minor amounts in pulp and paper, flue gas desulfurization, and water treatment (excluding soda ash consumption for glass manufacturing). As soda ash is consumed for these purposes, additional CO_2 is usually emitted. 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 trona production and soda ash consumption (see Table 4-41) between 1990 and 2013 were taken from USGS Minerals Yearbook for Soda Ash (1994 through 2013) and USGS Mineral Industry Surveys for Soda Ash (USGS 2014). Soda ash production and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-41: Soda Ash Production and Consumption Not Associated with Glass Manufacturing (kt)

Year	Production[a]	Consumption[b]
1990	14,700	3,351
2005	17,000	3,144
2009	15,100	2,647
2010	15,900	2,768
2011	16,500	2,663
2012	17,100	2,645
2013	17,400	2,674

[a] Soda ash produced from trona ore only.

[b] 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).

Uncertainty and Time-Series Consistency

Emission estimates from soda ash production have relatively low associated uncertainty levels in that reliable and accurate data sources are available for the emission factor and activity data. 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 2014a). 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 1995).The primary source of uncertainty, however, results from the fact that emissions from soda ash consumption 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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Soda Ash Production and Consumption CO_2 emissions were estimated to be between 2.5 and 2.9 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 6 percent above the emission estimate of 2.7 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production and Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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 and Consumption	CO_2	2.7	2.5	2.9	-7%	+6%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future Inventory reports are anticipated to estimate emissions from other uses of soda ash. To add specificity, future Inventory reports will extract soda ash consumed for other uses of carbonates from the current soda ash consumption emission estimates and include them under those sources.

In examining data from EPA's GHGRP to improve the emission estimates for Soda Ash and Consumption category, 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, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[168]

4.12 Petrochemical Production (IPCC Source Category 2B8)

The production of some petrochemicals results in the release of small amounts of CH_4 and CO_2 emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. 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 methanol and acrylonitrile are presented here and reported under IPCC Source Category 2B5. 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. Emissions from fuels and feedstocks transferred out of the system for use in energy purposes e.g. such as indirect or direct process heat or steam production are currently accounted for in the Energy Sector.

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,

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[168] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

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 also produces by-product CO_2, CO, and water from the direct oxidation of the propylene feedstock, and produces other hydrocarbons from side reactions in the ammoxidation process.

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 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 emissions are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Carbon black is also produced in the United States by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), by the thermal cracking of other hydrocarbons (i.e., thermal black process), and by the open burning of carbon black feedstock (i.e., lamp black process); each of these process are used at only one U.S. plant each (The Innovation Group 2004, 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 are also generated 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 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 by-product CO_2 produced from the direction 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. Worldwide approximately 70 percent of ethylene oxide produced 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 by-product 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 by-product 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 by-products (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; however, in the United States only two facilities use steam reforming of natural gas. 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 2013 were 26.5 MMT CO_2 Eq. (26,514 kt CO_2) and 0.1 MMT CO_2 Eq. (3 kt CH_4), respectively (see Table 4-43 and Table 4-44). Since 1990, the total CO_2 emissions from petrochemical production increased by approximately 23 percent. Methane emissions from petrochemical (methanol and acrylonitrile) production have decreased by approximately 63 percent since 1990, given declining production.

Table 4-43: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
CO_2	21.6	28.1	23.7	27.4	26.4	26.5	26.5
CH_4	0.2	0.1	+	0.1	+	0.1	0.1
Total	**21.9**	**28.3**	**23.8**	**27.4**	**26.4**	**26.5**	**26.6**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Emission totals may not add up due to rounding

Table 4-44: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
CO_2	21,633	28,124	23,706	27,388	26,396	26,477	26,514
CH_4	9	6	2	2	2	3	3

Methodology

Emissions of CO_2 and CH_4 were calculated using the estimation methods provided by the *2006 IPCC Guidelines* (IPCC 2006) and country specific methods from EPA's Greenhouse Gas Reporting Program (GHGRP). The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO_2 and CH_4 emissions from production of acrylonitrile and methanol, and a country specific approach similar to the IPCC Tier 2 method was used to estimate CO_2 emissions from carbon black, ethylene, ethylene oxide, and ethylene dichloride. The Tier 2 method for petrochemicals is a total feedstock carbon mass balance method used to estimate total CO_2 emissions but is not applicable for estimating CH_4 emissions. The Tier 2 mass balance 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. This method accounts for all the carbon as CO_2, including CH_4.

Carbon Black, Ethylene, Ethylene Dichloride and Ethylene Oxide

CO_2 emissions and national production were aggregated directly from the GHGRP data set for 2010 through 2013. In 2013, GHGRP data reported CO_2 emissions of 3,190,199 metric tons from carbon black production; 19,545,363 metric tons of CO_2 from ethylene production; 403,122 metric tons of CO_2 from ethylene dichloride production; and 1,395,936 metric tons of CO_2 from ethylene oxide production. 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, and ethylene oxide. Since 2010, EPA's GHGRP, under Subpart X, requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data) to facilitate verification of reported emissions. Under EPA's GHGRP, 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. The mass balance method is used by most facilities[169] and assumes that all the carbon input is converted into primary and secondary products, byproducts, 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.[170] More details on the GHG calculation and monitoring methods applicable to Petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).[171]

For prior years, for these petrochemical types, an average national CO_2 emission factor was calculated based on the 2010 through 2013 GHGRP data and applied to production for earlier years in the time series (1990 through 2009) to estimate CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide. CO_2 emission factors were derived from EPA's GHGRP by dividing annual CO_2 emissions for petrochemical type "i" with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2013 (EPA GHGRP 2014). 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 2010-2013 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 and ethylene dichloride for 1990 through 2009 were obtained from the American Chemistry Council's (ACC's) *Guide to the Business of Chemistry* (ACC 2002, 2003, 2005 through 2010). Annual production data for ethylene oxide were obtained from ACC's *U.S. Chemical Industry Statistical Handbook* for 2003 through 2009 (ACC 2014a) and from ACC's Business of Chemistry for 1990 through 2002 (ACC 2014b). As noted above, annual 2010 through 2013 production data for carbon black, ethylene, ethylene dichloride, and ethylene oxide, were obtained from EPA's GHGRP (EPA GHGRP 2014).

Acrylonitrile

CO_2 and CH_4 emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines* (IPCC 2006). Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2013. 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 2013 were obtained from ACC's Business of Chemistry (ACC 2014b).

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[169] A few facilities producing Ethylene Dichloride used CO_2 CEMS, which has been included in the aggregated GHGRP emissions.

[170] For ethylene processes only, because nearly all process emissions are from the combustion of process off-gas. Under GHGRP, Subpart X, ethylene facilities can report emissions from burning of process gases using the optional combustion methodology for ethylene production processes, which is requires estimating emissions based on fuel quantity and carbon contents of the fuel. This is consistent with the *2006 IPCC Guidelines* (p. 3.57) which recommends including combustion emissions from fuels obtained from feedstocks (e.g. off gases) in petrochemical production under in the IPPU sector.

[171] Available online at: http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>

Methanol

CO_2 and CH_4 emissions from methanol production were estimated using Tier 1 method in the *2006 IPCC Guidelines* (IPCC 2006). Annual methanol production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2013. Emission factors used to estimate methanol production emissions are as follows:

- 2.3 kg CH_4/metric ton methanol
- 0.67 metric tons CO_2/metric ton methanol

Annual methanol production data for 1990 through 2007 were obtained from the ACC Guide to the Business of Chemistry (ACC 2002, 2003, 2005 through 2011). The ACC discontinued its data series for methanol after 2007, so methanol production data for 2008 were obtained through the Methanol Institute (Jordan 2011). Methanol production data for 2009 through 2013 were obtained from Argus Media Inc. (Argus JJ&A 2014). ACC discontinued publication of this data due to confidentiality concerns given the small number of facilities producing methanol in the United States.

Table 4-45: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2009	2010	2011	2012	2013
Carbon Black	1,307	1,651	1,080	1,309	1,338	1,283	1,228
Ethylene	16,542	23,975	22,610	24,355	25,143	24,763	25,341
Ethylene Dichloride	6,283	11,260	8,120	8,149	8,621	11,309	11,462
Ethylene Oxide	2,429	3,220	2,580	2,925	3,014	3,106	3,148
Acrylonitrile	1,215	1,325	925	1,270	1,135	1,220	1,075
Methanol	3,785	2,336	790	778	685	1,015	1,350

Uncertainty and Time-Series Consistency

The CH_4 and CO_2 emission factors used for acrylonitrile and methanol 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 publication.

The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, and ethylene oxide 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. 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 uncertainty estimates for national methanol production quantity were obtained from Argus (Argus JJ&A 2014).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-46. Petrochemical production CO_2 emissions were estimated to be between 25.3 and 27.7 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 26.5 MMT CO_2 Eq. Petrochemical production CH_4 emissions were estimated to be between 0.03 and 0.10 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 54 percent below to 44 percent above the emission estimate of 0.08 MMT CO_2 Eq.

Table 4-46: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Carbon Black Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	26.5	25.3	27.7	-5%	+5%
Petrochemical Production	CH_4	0.08	0.03	0.10	-54%	+44%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculation Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each

greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in emissions from CH_4, HFCs, PFCs, SF_6, and NF_3. The GWP of N_2O has decreased, leading to a decrease in emissions. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

In addition, methodological recalculations were applied to the entire time series to ensure time series consistency. As noted above, emission information from EPA's GHGRP were used to update estimates. Average country-specific CO_2 emission factors were derived from the 2010 through 2013 GHGRP data for carbon black, ethylene, ethylene dichloride, and ethylene oxide. Annual production and CO_2 emission factor data were obtained from EPA's GHGRP for 2010 through 2013, and were used to estimate emissions for 2010 through 2013. An average CO_2 emission factor was calculated from the 2010 through 2013 GHGRP data and was used to estimate emissions for 1990 through 2009 for carbon black, ethylene, ethylene dichloride, and ethylene oxide using historic production data compiled for 1990 through 2009 (ACC 2014a; ACC 2014b).

Note, ethylene oxide is included in the IPCC petrochemical production source category but had not been included in previous versions of this Inventory due to lack of publicly-available data. Similarly, acrylonitrile is included in the IPCC Petrochemical Production source category but had not been included in the previous Inventory due to lack of publicly-available data. Annual acrylonitrile production data for 1990 through 2013 was obtained from ACC (ACC 2014b). CO_2 and CH_4 emissions from acrylonitrile were estimated using the IPCC default Tier 1 emission factors and annual acrylonitrile production.

For the previous Inventory, only CH_4 emissions were estimated for methanol using the IPCC default Tier 1 emission factor. For the current Inventory, CO_2 emissions were also estimated for methanol using the IPCC default Tier 1 CO_2 emission factor. In the current version of the Inventory, updated methanol production data were made available through Argus (Argus JJ&A 2014) for the years 2009 through 2012. This update reflected in a decrease of CH_4 emissions from Methanol production.

Planned Improvements

Pending resources, a potential improvement to the inventory estimates for this source category would focus on analyzing 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. Some degree of double counting may occur between CO_2 estimates of non-energy use of fuels in the energy sector and CO_2 process emissions from petrochemical production in this sector. Data integration is not feasible at this time as feedstock data from EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries (e.g., petrochemical production). EPA, through GHGRP, currently does not collect complete data on quantities of fuel consumed as feedstocks by petrochemical producers, only feedstock type. Updates to reporting requirements may address this issue future reporting years for the GHGRP data allowing for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter.

4.13 HCFC-22 Production (IPCC Source Category 2B9a)

Trifluoromethane (HFC-23 or CHF_3) is generated as a byproduct during the manufacture of chlorodifluoromethane (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 is scheduled to be phased out by 2020 under the U.S. Clean Air Act.[172] Feedstock production, however, is permitted to continue indefinitely.

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 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 U.S. in 2013. Emissions of HFC-23 from this activity in 2013 were estimated to be 4.1 MMT CO_2 Eq. (0.3 kt) (see Table 4-47). This quantity represents a 25 percent decrease from 2012 emissions and a 91 percent decline from 1990 emissions. The decrease from 2012 emissions and the decrease from 1990 emissions were caused by a decrease in HCFC-22 production and a decrease in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The 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, and (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 factor was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

Table 4-47: HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and kt HFC-23)

Year	MMT CO_2 Eq.	kt HFC-23
1990	46.1	3
2005	20.0	1
2009	6.8	0.5
2010	8.0	0.5
2011	8.8	0.6
2012	5.5	0.4
2013	4.1	0.3

Note: Emission values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values

Methodology

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. Emissions for 2010 through 2013 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's 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.

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[172] 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]

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 to estimate their emissions 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. Plants that release (or historically have released) some of their byproduct HFC-23 periodically measure HFC-23 concentrations in the output stream 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, 2010). To estimate 2010 through 2013 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through the 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, and also for 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 4-48.

Table 4-48: HCFC-22 Production (kt)

Year	kt
1990	139
2005	156
2009	91
2010	101
2011	110
2012	96
2013	C

Note: HCFC-22 production in 2013 is considered Confidential Business Information (CBI) as there were only two producers of HCFC-22 in 2013.

Uncertainty and Time-Series Consistency

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 2013. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the three plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants may have changed between 2006 and 2013 (because both HCFC-22 production and the HFC-23 emission rate declined significantly), the two plants that contribute significantly to emissions were estimated to have similar relative uncertainties in their 2006 (as well as 2005) emission estimates. Thus, changes in the relative contributions of these two plants to total emissions are 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 4-49. HFC-23 emissions from HCFC-22 production were estimated to be between 3.8 and 4.5 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 4.1 MMT CO_2 Eq.

Table 4-49: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	4.1	3.8	4.5	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories), which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWP of HFC-23 has increased, leading to an overall increase in emissions. For more information please see the Recalculations and Improvements Chapter.

4.14 Carbon Dioxide Consumption (IPCC Source Category 2B10)

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). Carbon dioxide used for EOR is injected into the underground reservoirs to increase the reservoir pressure to enable additional petroleum to be produced. For the most part, CO_2 used in non-EOR applications will eventually be released to the atmosphere, and for the purposes of this analysis CO_2 used in commercial applications other than EOR is assumed to be emitted to the atmosphere. Carbon dioxide used in EOR applications is discussed in the Energy Chapter under “Carbon Capture and Storage, including Enhanced Oil Recovery” and is not discussed in this section.

CO_2 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. Only CO_2 produced from naturally occurring CO_2 reservoirs and used in industrial applications other than EOR is included in this analysis. Neither byproduct CO_2 generated from energy nor industrial production processes nor CO_2 separated from crude oil and natural gas are included in this analysis for a number of reasons. Carbon dioxide captured from biogenic sources (e.g., ethanol production plants) is not included in the inventory. Carbon dioxide captured from crude oil and gas production is used in EOR applications and is therefore reported in the Energy Chapter. Any CO_2 captured from industrial or energy production processes (e.g., ammonia plants, fossil fuel combustion) and used in non-EOR applications is assumed to be emitted to the atmosphere. The CO_2 emissions from such capture and use are therefore accounted for under Ammonia Production, Fossil Fuel Combustion, or other appropriate source category.[173]

CO_2 is produced as a byproduct of crude oil and natural gas production. This CO_2 is separated from the crude oil and natural gas using gas processing equipment, and may be emitted directly to the atmosphere, or captured and reinjected into underground formations, used for EOR, or sold for other commercial uses. A further discussion of CO_2 used in EOR is described in the Energy Chapter under the text box titled "Carbon Dioxide Transport, Injection, and Geological Storage." The only CO_2 consumption that is accounted for in this analysis is CO_2 produced from naturally-occurring CO_2 reservoirs that is used in commercial applications other than EOR.

There are currently three facilities, one in Mississippi (Jackson Dome) and two in New Mexico (Bravo Dome and West Bravo Dome), producing CO_2 from naturally-occurring CO_2 reservoirs for use in both EOR and in other commercial applications (e.g., chemical manufacturing, food production). A fourth facility in Colorado (McCallum Dome**)** is producing CO_2 from naturally occurring CO_2 reservoirs for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006). There are other naturally-occurring CO_2 reservoirs, mostly located in the western United States, that produce CO_2, but they are only producing CO_2 for EOR applications, not for other commercial applications (Allis et al. 2000). Carbon dioxide production from these facilities is discussed in the Energy Chapter.

In 2013, the amount of CO_2 produced by the Colorado, Mississippi, and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere was 0.9 MMT CO_2 Eq. (903 kt) (see Table 4-50). This is an increase of 7 percent from the previous year and a decrease of 39 percent since 1990.

Table 4-50: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,472
2005	1.4	1,375
2009	1.8	1,795
2010	1.2	1,206
2011	0.8	802
2012	0.8	841
2013	0.9	903

Methodology

CO_2 emission estimates for 1990 through 2013 were based on production data for the four facilities currently producing CO_2 from naturally-occurring CO_2 reservoirs for use in non-EOR applications. 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 production). It is assumed that 100 percent of the CO_2 production used in commercial applications other than EOR is eventually released into the atmosphere.

CO_2 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, from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for 2001 to 2009, and from EPA's GHGRP data for 2010 through 2013 (EPA 2014) (see Table 4-51). 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 1990-1999. Carbon dioxide production data for the Bravo Dome, New Mexico facilities were obtained from ARI for 1990 through 2009 (ARI 1990-2010), and from

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[173] There are currently four known electric power plants operating in the United States that capture CO_2 for use as food-grade CO_2 or other industrial processes; however, insufficient data prevents estimating emissions from these activities as part of CO_2 Consumption.

EPA's GHGRP data for 2010 through 2013 (EPA 2014). Data for the West Bravo Dome facility were only available starting 2009 (i.e., only for 2009 through 2013). The percentage of total production that was used for non-EOR applications for 2010 through 2013 was obtained from EPA's GHGRP (EPA 2014) data. The percentage of total production that was used for non-EOR applications for the Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003 and 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 2013 (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 4-51: 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)
1990	1,344 (100%)	63 (1%)	+	65 (100%)
2005	1,254 (27%)	58 (1%)	+	63 (100%)
2009	1,705 (13%)	46 (1%)	21 (1%)	23 (100%)
2010	1,156 (21%)	+	+	50 (100%)
2011	770 (15%)	+	+	32 (100%)
2012	808 (16%)	+	+	33 (100%)
2013	891[174]	+	+	12 (100%)

+ Does not exceed 0%.

Uncertainty and Time-Series Consistency

Uncertainty is associated with the number of facilities that are currently producing CO_2 from naturally occurring CO_2 reservoirs for commercial uses other than EOR, and for which the CO_2 emissions are not accounted for elsewhere. Research indicates that there are only two such facilities, which are in New Mexico and Mississippi; however, additional facilities may exist that have not been identified. In addition, it is possible that CO_2 recovery exists in particular production and end-use sectors that are not accounted for elsewhere. Such recovery may or may not affect the overall estimate of CO_2 emissions from that sector depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether CO_2 is being recovered from other facilities for application to end uses that are not accounted for elsewhere.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-52. Carbon dioxide consumption CO_2 emissions for 2013 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 12 percent below to 13 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-52: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	0.9	0.8	1.1	-12%	+13%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

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[174] CO_2 quantity used for EOR applications is not yet available. The indicated quantity (891 kt) for Jackson Dome is for non-EOR applications only.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Relative to the previous Inventory, 1990 through 2009 CO_2 consumption data for the McCallum Dome facility in Colorado was corrected after a unit conversion error was identified. The revised time-series data were double checked against data reported by the Colorado Oil and Gas Conservation Commissions (COGCC 1990-2013). This revision caused an increase in CO_2 emissions for McCallum Dome for 1990 through 2009.

Planned Improvements

CO_2 production data for 1990 through 1998 for McCallum dome needs to be compiled and improved. Currently, only 1999 through 2013 data is available online (COGCC 2014). Similarly, 1990 through 1999 production data for the Jackson Dome facility is not publicly available and needs to be compiled. For example, the information could be in hard copy records at the Oil and Gas Conservation Commission and a request or site visit is required to gather the data.

4.15 Phosphoric Acid Production (IPCC 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 CO_2 emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock.

Phosphate rock is mined in Florida, North Carolina, Idaho, Utah, and other areas of the United States and is used primarily as a raw material for phosphoric acid production.

The composition of natural phosphate rock varies depending upon 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 also may contain organic carbon.

The calcium carbonate component of the phosphate rock is integral to the phosphate rock chemistry. Phosphate rock can also contain organic carbon that is physically incorporated into the mined rock but is not an integral component of the phosphate rock chemistry.

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). However, the generation of CO_2 is due to the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \bullet 2H_2O + CO_2$$

Total U.S. phosphate rock production sold or used in 2013 was 29.0 million metric tons (USGS 2014). Approximately 80 percent of domestic phosphate rock production was mined in Florida and North Carolina (8 mines total), while the remaining 20 percent of production was mined in Idaho and Utah (5 mines total). Total imports of phosphate rock in 2013 were 2.6 million metric tons (USGS 2014). Most of the imported phosphate rock (70 percent) is from Morocco, with the remaining 30 percent being from Peru (USGS 2014). All phosphate rock mining companies are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines. Some additional phosphoric acid production facilities are located in Texas, Louisiana, and Mississippi that used imported phosphate rock.

Over the 1990 to 2013 period, domestic production has decreased by nearly 42 percent. Total CO_2 emissions from phosphoric acid production were 1.2 MMT CO_2 Eq. (1,173 kt) in 2013 (see Table 4-53). Domestic consumption of phosphate rock in 2013 was estimated to have increased by approximately 4 percent over 2012 levels, owing to increased production of phosphoric acid (USGS 2014).

Table 4-53: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.6	1,586
2005	1.4	1,395
2009	1.0	1,016
2010	1.1	1,130
2011	1.2	1,198
2012	1.1	1,138
2013	1.2	1,173

Methodology

CO_2 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:

$$E_{pa} = C_{pr} \times Q_{pr}$$

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 is based on the assumption that all of the inorganic carbon (calcium carbonate) content of the phosphate rock reacts to 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 *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 4-54). For the years 1990 through 1992, and 2005 through 2013, 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 average share of U.S. production in those states from 1993 to 2004 data. For the years 2005 through 2013, the same approximation method is used, but the share of U.S. production in those states data were obtained from the USGS commodity specialist for phosphate rock (USGS 2012). Data for domestic sales or consumption of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption for 1990 through 2013 were obtained from *USGS Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2013), and from *USGS Minerals Commodity Summaries: Phosphate Rock in 2013* (USGS 2014). From 2004 through 2013, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005 through 2014).

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 (FIPR 2003). Phosphate rock mined in Florida contains approximately 1 percent inorganic carbon, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic carbon. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic carbon, respectively (see Table 4-55).

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 (80 percent of domestic production) and carbonate content data for phosphate rock mined in Morocco are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation is based on the assumption 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 2012b).

Table 4-54: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990	2005	2009	2010	2011	2012	2013
U.S. Domestic Consumption[a]	49,800	35,200	25,500	28,100	28,600	27,300	29,000
FL and NC	42,494	28,160	20,400	22,480	22,880	21,840	23,200
ID and UT	7,306	7,040	5,100	5,620	5,720	5,460	5,800
Exports—FL and NC	6,240	+	+	+	+	+	+
Imports	451	2,630	2,000	2,400	3,350	3,080	2,600
Total U.S. Consumption	**44,011**	**37,830**	**27,500**	**30,500**	**31,950**	**30,380**	**31,600**

Table 4-55: Chemical Composition of Phosphate Rock (Percent by weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00

Source: FIPR 2003

Uncertainty and Time-Series Consistency

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 2013. For previous years in the time series, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was reported. Regional production for 2013 was estimated based on regional production data from previous years and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2013 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 calculation are reported 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.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock, 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 2003) of chemical composition of the phosphate rock; limited data is available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of the FIPR indicated that in the phosphoric acid production process, the organic C 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 2003a). 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 C 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 approximately 7 percent of domestically-produced phosphate rock is used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2006). 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 is based on the assumption 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 4-56. Phosphoric acid production CO_2 emissions were estimated to be between 1.0 and 1.4 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 21 percent above the emission estimate of 1.2 MMT CO_2 Eq.

Table 4-56: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Phosphoric Acid Production	CO_2	1.2	1.0	1.4	-19%	+21%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Relative to the previous Inventory, the phosphate rock consumption data (sold or used and imports for consumption) for 2012 were revised based on updated data publicly available from USGS (2014). This revision caused an increase in the 2012 emission estimate by approximately 3 percent.

Planned Improvements

Pending resources, a potential improvement to the Inventory estimates for this source category would include direct integration of GHGRP data for 2010 through 2013 and use of reported GHGRP data to update the inorganic C content of phosphate rock for prior years. In order to provide estimates for the entire time series (i.e. 1990 through 2009), the applicability of the averaged inorganic C content data (by region) from 2010 through 2013 GHGRP data to previous years' estimates will need to be evaluated. 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.[175]

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[175] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

4.16 Iron and Steel Production (IPCC Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of CO_2 and CH_4 as raw materials are refined into iron and then transformed into crude steel. Emissions from conventional fuels (e.g., natural gas, fuel oil, etc.) consumed for energy purposes during the production of iron and steel are accounted for in the Energy chapter.

Iron and steel production includes six distinct production processes: coke production, sinter production, direct reduced iron (DRI) production, pig iron production, electric arc furnace (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. 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, etc.) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold for use as synthetic natural gas are deducted and reported in the Energy chapter. 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, etc.). In addition, fugitive CH_4 emissions are also generated by the coke production, sinter production, and pig iron production processes.

Currently, there are between 15 and 20 integrated iron and steel steelmaking facilities that utilize BOFs to refine and produce steel from iron and more than 100 steelmaking facilities that utilize EAFs to produce steel primarily from recycled ferrous scrap. In addition, there are 18 cokemaking facilities, of which 7 facilities are co-located with integrated iron and steel facilities. Nearly 62 percent of the raw steel produced in the United States is produced in one of seven states: Alabama, Arkansas, Indiana, Kentucky, Mississippi, Ohio, and Tennessee.

Total production of crude steel in the United States between 2000 and 2008 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. In 2010, crude steel production rebounded to 88,731,000 tons as economic conditions improved and then continued to increase to 95,237,000 tons in 2011 and 97,770,000 tons in 2012; crude steel production slightly decreased to 95,766,000 tons in 2013 (AISI 2014a). The United States was the third largest producer of raw steel in the world, behind China and Japan, accounting for approximately 5.4 percent of world production in 2013 (AISI 2014a).

The majority of CO_2 emissions from the iron and steel production process come from the use of coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of flux and from the removal of C from pig iron used to produce steel.

According to the *2006 IPCC Guidelines* (IPCC 2006), 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. Therefore, 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 IPPU sector. However, the approaches and emission estimates for both metallurgical coke production and iron and steel production are both presented here because the activity data used to estimate emissions from metallurgical coke production have significant overlap with activity data used to estimate iron and steel production emissions. In addition, some byproducts (e.g., coke oven gas, etc.) 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, etc.) 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 fuels (e.g., natural gas, fuel oil, etc.) 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 and CH_4 from metallurgical coke production in 2013 were 1.8 MMT CO_2 Eq. (1,822 kt) and less than 0.05 MMT CO_2 Eq. (less than 0.5 kt), respectively (see Table 4-57 and Table 4-58), totaling 1.8 MMT CO2 Eq. Emissions increased in 2013 from 2012 levels, but have decreased overall since 1990. In 2013, domestic coke production increased by 1 percent from the previous year, and has decreased overall since 1990. Coke production in 2013 was 26 percent lower than in 2000 and 45 percent below 1990. Overall, emissions from metallurgical coke production have declined by 26 percent (0.6 MMT CO_2 Eq.) from 1990 to 2013.

Table 4-57: CO_2 and CH_4 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2009	2010	2011	2012	2013
CO_2	2.5	2.0	1.0	2.1	1.4	0.5	1.8
CH_4	+	+	+	+	+	+	+
Total	**2.5**	**2.0**	**1.0**	**2.1**	**1.4**	**0.5**	**1.8**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

\+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-58: CO_2 and CH_4 Emissions from Metallurgical Coke Production (kt)

Gas	1990	2005	2009	2010	2011	2012	2013
CO_2	2,470	2,043	956	2,084	1,425	542	1,822
CH_4	+	+	+	+	+	+	+

\+ Does not exceed 0.5 kt

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2013 were 50.5 MMT CO_2 Eq. (50,466 kt) and 0.7 MMT CO_2 Eq. (27.7 kt), respectively (see Table 4-59 through Table 4-62), totaling approximately 51.2 MMT CO_2 Eq. Emissions decreased in 2013 and have decreased overall 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.

In 2013, domestic production of pig iron decreased by 5 percent from 2012 levels. Overall, domestic pig iron production has declined since the 1990s. Pig iron production in 2013 was 37 percent lower than in 2000 and 39 percent below 1990. Carbon dioxide emissions from steel production have increased by 8 percent (0.7 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 48 percent (46.8 MMT CO_2 Eq.) from 1990 to 2013.

Table 4-59: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2009	2010	2011	2012	2013
Sinter Production	2.4	1.7	0.8	1.0	1.2	1.2	1.1
Iron Production	47.6	19.4	15.9	19.1	19.9	12.6	13.4
Steel Production	8.0	9.4	7.6	9.2	9.3	9.9	8.6
Other Activities[a]	39.3	34.2	17.8	24.3	28.2	30.2	27.3
Total	**97.3**	**64.6**	**42.1**	**53.7**	**58.6**	**53.8**	**50.5**

[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 4-60: CO_2 Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990	2005	2009	2010	2011	2012	2013
Sinter Production	2,448	1,663	763	1,045	1,188	1,159	1,117
Iron Production	47,650	19,414	15,941	19,109	19,901	12,557	13,411

Steel Production	7,958	9,386	7,555	9,248	9,262	9,874	8,629
Other Activities[a]	39,256	34,160	17,815	24,260	28,232	30,195	27,309
Total	**97,311**	**64,623**	**42,073**	**53,662**	**58,583**	**53,786**	**50,466**

[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 4-61: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
Sinter Production	+	+	+	+	+	+	+
Iron Production	1.1	0.8	0.4	0.6	0.7	0.7	0.7
Total	**1.1**	**0.9**	**0.4**	**0.6**	**0.7**	**0.7**	**0.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

\+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-62: CH_4 Emissions from Iron and Steel Production (kt)

Source/Activity Data	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
Sinter Production	0.9	0.6	0.3	0.4	0.4	0.4	0.4
Iron Production	44.7	33.5	17.1	24.2	27.2	28.9	27.3
Total	**45.6**	**34.1**	**17.4**	**24.5**	**27.6**	**29.3**	**27.7**

Methodology

Emission estimates presented in this chapter are largely based on Tier 2 methodologies provided by the *2006 IPCC Guidelines* (IPCC 2006). 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. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production and DRI production) for which available data are insufficient for utilizing a Tier 2 method.

The Tier 2 methodology equation is as follows:

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b)\right] \times \frac{44}{12}$$

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 material *a*, metric tons C/metric ton material

Q_b = Quantity of output material *b*, metric tons

C_b = Carbon content of 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:

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,p} = Q_d \times EF_{d,p}$$

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
$E_{d,p}$ = Emissions from DRI production process for pollutant p (CO_2 or CH_4), metric ton
Q_d = Quantity of DRI produced, metric tons
$EF_{d,p}$ = Emission factor for pollutant p (CO_2 or CH_4), metric ton p/metric ton DRI

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical (coal) coke that 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 emission from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* (IPCC 2006) was utilized. The amount of C contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze, coke oven gas, and coal tar) 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). Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of C contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-63). 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 (AISI 2008c; 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 4-63: Material Carbon Contents for Metallurgical Coke Production

Material	**kg C/kg**
Coal Tar	0.62
Coke	0.83
Coke Breeze	0.83
Coking Coal	0.73
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.

The production processes for metallurgical coke production 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 (0.1g CH_4 per metric ton of coke production) taken from the *2006 IPCC Guidelines* (IPCC 2006) for metallurgical coke production.

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 2014d) (see Table 4-64). 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 2014a) and through personal communications with AISI (2008c) (see Table 4-65). The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (2008c). 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 coking coal, metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines* (IPCC 2006). The carbon content for coke breeze was assumed to equal the C content of coke.

Table 4-64: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2009	2010	2011	2012	2013
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	13,904	19,135	19,445	18,825	19,481
Coke Production at Coke Plants	25,054	15,167	10,109	13,628	13,989	13,764	13,898
Coal Breeze Production	2,645	1,594	1,043	1,435	1,458	1,412	1,461
Coal Tar Production	1,058	638	417	574	583	565	584

Table 4-65: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (million ft^3)

Source/Activity Data	1990	2005	2009	2010	2011	2012	2013
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	66,155	95,405	109,044	113,772	108,162
Natural Gas Consumption	599	2,996	2,121	3,108	3,175	3,267	3,247
Blast Furnace Gas Consumption	24,602	4,460	2,435	3,181	3,853	4,351	4,255

Iron and Steel Production

Emissions of CO_2 from sinter production and direct reduced iron production were estimated by multiplying total national sinter production and the total national direct reduced iron production by Tier 1 CO_2 emission factors (see Table 4-66). Because estimates of sinter production and direct reduced iron production were not available, production was assumed to equal consumption.

Table 4-66: CO_2 Emission Factors for Sinter Production and Direct Reduced Iron Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7

Source: IPCC 2006, Table 4.1.

To estimate emissions from pig iron production in the blast furnace, the amount of C contained in the produced pig iron and blast furnace gas were deducted from the amount of C contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, and direct coal injection). The C contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific C content by each material type (see Table 4-67). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process.

Emissions from steel production in EAFs were estimated by deducting the C contained in the steel produced from the C contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of C from direct reduced iron, pig iron, and flux additions to the EAFs were also included in the EAF calculation. For BOFs, estimates of C contained in BOF steel were deducted from C contained in inputs such as natural gas, coke oven gas, fluxes, and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-67). 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 [AISI 2008c]). The amount of flux (e.g., limestone and dolomite) used during steel manufacture was deducted from the Other Process Uses of Carbonates source category to avoid double-counting.

CO_2 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 4-67).

CO_2 emissions associated with the sinter production, direct reduced iron 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 4-59 and Table 4-60).

Table 4-67: 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.

The production processes for sinter and pig iron result 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* (IPCC 2006) for sinter production and the *1995 IPCC Guidelines* (IPCC/UNEP/ OECD/IEA 1995) (see Table 4-68) for pig iron production. The production of direct reduced iron also results in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas); however, these emission estimates are excluded due to data limitations.

Table 4-68: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Pig Iron	0.9	g CH_4/kg
Sinter	0.07	kg CH_4/metric ton

Source: Sinter (IPCC 2006, Table 4.2), Pig Iron (IPCC/UNEP/OECD/IEA 1995, Table 2.2)

Sinter consumption data for 1990 through 2013 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2014a) and through personal communications with AISI (2008c) (see Table 4-69). In general, direct reduced iron (DRI) consumption data were obtained from the *USGS Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2013) and personal communication with the USGS Iron and Steel Commodity Specialist (Fenton 2014). However, 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. Also, 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 and direct reduced iron 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 2014a) and through personal communications with AISI (2008c) (see Table 4-69 and Table 4-70).

Data for EAF steel production, flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2014a) and through personal communications with AISI (2006 through 2014b and 2008c). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (AISI 2008c). Data for BOF steel production, 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 2014a) and through personal communications with AISI (2008c). 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 2013). 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 2014a) and through personal communications with AISI (2008c).

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's Natural Gas Annual 2011 (EIA 2012b). 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* (IPCC 2006). The C contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (2013c) and EPA (2010). Heat contents for the same fuels were obtained from EIA (1992, 2013a). Heat contents for coke oven gas and blast furnace gas were provided in Table 2-2 of the report, *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000).

Table 4-69: 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	2009	2010	2011	2012	2013
Sinter Production							
Sinter Production	12,239	8,315	3,814	5,225	5,941	5,795	5,583
Direct Reduced Iron Production							
Direct Reduced Iron Production	516	1,303	1,165	1,441	1,582	3,530	3,350
Pig Iron Production							
Coke Consumption	24,946	13,832	8,572	10,883	11,962	9,571	9,308
Pig Iron Production	49,669	37,222	19,019	26,844	30,228	32,063	30,309
Direct Injection Coal Consumption	1,485	2,573	1,674	2,279	2,604	2,802	2,675
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	845	1,189	1,257	1,318	1,122
Scrap Steel Consumption	42,691	46,600	43,200	47,500	50,500	50,900	47,327
Flux Consumption	319	695	476	640	726	748	771
EAF Steel Production	33,511	52,194	36,725	49,339	52,108	52,415	52,641
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	25,900	31,200	31,300	31,500	29,570
Scrap Steel Consumption	14,713	11,400	7,110	9,860	8,800	8,350	7,894
Flux Consumption	576	582	318	431	454	476	454
BOF Steel Production	43,973	42,705	22,659	31,158	34,291	36,282	34,238

Note: Emissions values are presented in CO$_2$ equivalent mass units using IPCC AR4 GWP values.

Table 4-70: 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	2009	2010	2011	2012	2013
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	35,933	47,814	59,132	62,469	48,812
Fuel Oil Consumption (thousand gallons)	163,397	16,170	23,179	27,505	21,378	19,240	17,468
Coke Oven Gas Consumption	22,033	16,557	9,951	14,233	17,772	18,608	17,710
Blast Furnace Gas Production	1,439,380	1,299,980	672,486	911,180	1,063,326	1,139,578	1,026,973

EAF Steel Production							
Natural Gas Consumption	15,905	19,985	7,848	10,403	6,263	11,145	10,514
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	373	546	554	568	568
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	55,831	80,626	90,718	94,596	89,884
Blast Furnace Gas Consumption	1,414,778	1,295,520	670,051	907,999	1,059,473	1,135,227	1,022,718

Uncertainty and Time-Series Consistency

The estimates of CO_2 and CH_4 emissions from metallurgical coke production are based on 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 C contents. There is uncertainty associated with the assumption that direct reduced iron and sinter consumption are equal to production. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal; some of this coal may be used for electricity generation. There is also uncertainty associated with the C contents for pellets, sinter, and natural ore, which are assumed to equal the carbon contents of direct reduced iron. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge C 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 C contents produce a relatively accurate estimate of CO_2 emissions. However, there are uncertainties associated with each.

For the purposes of the CH_4 calculation from iron and steel production it is assumed that all of the CH_4 escapes as fugitive emissions and that none of the CH_4 is captured in stacks or vents. Additionally, the CO_2 emissions calculation is not corrected by subtracting the C content of the CH_4, which means there may be a slight double counting of C as both CO_2 and CH_4.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-71 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production were estimated to be between 43.3 and 61.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below and 17 percent above the emission estimate of 52.3 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production were estimated to be between 0.5 and 0.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below and 22 percent above the emission estimate of 0.7 MMT CO_2 Eq.

Table 4-71: 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	2013 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	52.3	43.3	61.2	-17%	+17%
Metallurgical Coke & Iron and Steel Production	CH_4	0.7	0.5	0.8	-21%	+22%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements involve evaluating and analyzing data reported under EPA's GHGRP to improve the emission estimates for the Iron and Steel Production source category. Particular attention would 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, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[176]

Additional improvements include accounting for emission estimates for the production of metallurgical coke to 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 inputs for preparing Tier 2 estimates for sinter and direct reduced iron production, as well as identifying information to better characterize emissions from the use of process gases and fuels within the Energy and Industrial Processes chapters.

4.17 Ferroalloy Production (IPCC Source Category 2C2)

Carbon dioxide and CH_4 are emitted from the production of several ferroalloys. Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). Emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for in 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 here because of the small number of manufacturers of these materials in the United States, and therefore, government information disclosure rules prevent the publication of production data for these production facilities.

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[176] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

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 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:

$$\mathrm{Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO}$$

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.

When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Ferroalloys are used primarily by the iron and steel industry, and production trends closely follow that of the iron and steel industry. Fewer than 10 facilities in the United States produce ferroalloys.

Emissions of CO_2 from ferroalloy production in 2013 were 1.8 MMT CO_2 Eq. (1,785 kt) (see Table 4-72 and Table 4-73), which is a 17 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2013 were 0.01 MMT CO_2 Eq. (0.5 kt CH_4), which is a 26 percent decrease since 1990.

Table 4-72: CO_2 and CH_4 Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990	2005	2009	2010	2011	2012	2013
CO_2	2.2	1.4	1.5	1.7	1.7	1.9	1.8
CH_4	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**1.5**	**1.7**	**1.7**	**1.7**	**1.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-73: CO_2 and CH_4 Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2009	2010	2011	2012	2013
CO_2	2,152	1,392	1,469	1,663	1,735	1,903	1,785
CH_4	1	+	+	+	+	1	+

+ Does not exceed 0.5 kt

Methodology

Emissions of CO_2 and CH_4 from ferroalloy production were calculated using a Tier 1 method from the *2006 IPCC Guidelines* (IPCC 2006) by multiplying annual ferroalloy production by material-specific default emission factors provided by IPCC (2006). Default emission factors were used because country-specific emission factors are not currently available.

For ferrosilicon alloys containing 25 to 55 percent silicon and miscellaneous alloys (including primarily magnesium-ferrosilicon, but also including other silicon alloys) containing 32 to 65 percent silicon, an emission factor for 45 percent silicon was applied for CO_2 (i.e., 2.5 metric tons CO_2/metric ton of alloy produced) and an emission factor for 65 percent silicon was applied for CH_4 (i.e., 1 kg CH_4/metric ton of alloy produced). Additionally, for ferrosilicon alloys containing 56 to 95 percent silicon, an emission factor for 75 percent silicon ferrosilicon was applied for both CO_2 and CH_4 (i.e., 4 metric tons CO_2/metric ton alloy produced and 1 kg CH_4/metric ton of alloy produced, respectively). The emission factors for silicon metal equaled 5 metric tons CO_2/metric ton metal produced and 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 C and 10 percent inert material (Onder and Bagdoyan 1993).

Ferroalloy production data for 1990 through 2013 (see Table 4-74) were obtained from the USGS through the *Minerals Yearbook: Silicon* (USGS 1996 through 2013) and the *Mineral Industry Surveys: Silicon in September 2014* (USGS 2014). The following data were available from the USGS publications for the time-series:

- Ferrosilicon, 25%-55% Si: Annual production data were available from 1990-2010.

- Ferrosilicon, 56%-95% Si: Annual production data were available from 1990-2010.
- Silicon Metal: Annual production data were available from 1990-2005. The production data for 2005 were used as proxy for 2006-2010.
- Miscellaneous Alloys, 32%-65% Si: Annual production data were available from 1990-1999. Starting 2000, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS reported 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/total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2013 (USGS 2013, 2014). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

Table 4-74: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 25%-55%	Ferrosilicon 56%-95%	Silicon Metal	Misc. Alloys 32-65%
1990	321,385	109,566	145,744	72,442
2005	123,000	86,100	148,000	NA
2009	123,932	104,855	148,000	NA
2010	153,000	135,000	148,000	NA
2011	159,667	140,883	154,450	NA
2012	175,108	154,507	169,385	NA
2013	164,229	144,908	158,862	NA

NA (Not Available for product type, aggregated along with ferrosilicon, 25%-55% Si)

Uncertainty and Time-Series Consistency

Annual ferroalloy production was reported by the USGS in three broad categories till 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 proxy for 2005 through 2010). Starting with the 2011 minerals yearbook, 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.

Also, some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants), 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.[177] 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 will

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[177] Emissions and sinks of biogenic carbon are accounted for in the *Land Use, Land-Use Change, and Forestry* chapter.

reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-75. Ferroalloy production CO_2 emissions were estimated to be between 1.6 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 1.8 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 12 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-75: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	1.8	1.6	2.0	-12%	+12%
Ferroalloy Production	CH_4	+	+	+	-12%	+12%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 MMT CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Starting in 2011, USGS ceased publication of ferrosilicon production data disaggregated by product type. Instead, total silicon materials production was reported for 2011 through 2013. The previous versions of the Inventory used 2010 production data (by product type) as proxy for 2011 and 2012. In this version of the Inventory, production shares by product type were developed using the 2010 production data (by product type). These ferrosilicon product shares were applied to the total ferrosilicon production quantity to estimate annual production by product type for 2011 through 2013.

Planned Improvements

According to the *2006 IPCC Guidelines* (IPCC 2006), emission factors are provided for a total of nine different ferroalloy types: four grades of ferrosilicon (FeSi) (i.e., 45, 65, 75, and 90 percent Si), two grades of ferromanganese (FeMn) (i.e., 1 and 7 percent C), silicomanganese (SiMn), ferrochromium (FeCr), and silicon metal. However, due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules, the current availability of ferroalloy production data is quite limited (Tuck 2013). Additional research is being conducting to assess the feasibility of obtaining alternative activity data.

Future improvements involve evaluating and analyzing data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Ferroalloy Production source category. Particular attention would 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, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[178]

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[178] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

4.18 Aluminum Production (IPCC Source Category 2C3)

Aluminum is a light-weight, 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 fourth largest producer of primary aluminum, with approximately 4 percent of the world total production (USGS 2014). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of CO_2 and two perfluorocarbons (PFCs): Perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

CO_2 is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult 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 lining that serves as the cathode. Carbon is also contained in the anode, which can be a C mass of paste, coke briquettes, or prebaked C blocks from petroleum coke. During reduction, most of this C is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 3.3 MMT CO_2 Eq. (3,255 kt) in 2013 (see Table 4-76). The C 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 4-76: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	6.8	6,831
2005	4.1	4,142
2009	3.0	3,009
2010	2.7	2,722
2011	3.3	3,292
2012	3.4	3,439
2013	3.3	3,255

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 "anode effects." These anode effects cause C 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.

Since 1990, emissions of CF_4 and C_2F_6 have declined by 87 percent and 81 percent, respectively, to 2.3 MMT CO_2 Eq. of CF_4 (0.31 kt) and 0.7 MMT CO_2 Eq. of C_2F_6 (0.05 kt) in 2013, as shown in Table 4-77 and Table 4-78. 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 52 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 71 percent. Emissions increased by approximately 1 percent between 2012 and 2013 due to a slight increase in both CF_4 and C_2F_6 emissions per metric ton of aluminum produced.

Table 4-77: PFC Emissions from Aluminum Production (MMT CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	17.9	3.5	21.5
2005	2.9	0.6	3.4
2009	1.5	0.4	1.9
2010	1.4	0.5	1.9
2011	2.7	0.8	3.5
2012	2.3	0.7	2.9
2013	2.3	0.7	3.0

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding.

Table 4-78: PFC Emissions from Aluminum Production (kt)

Year	CF_4	C_2F_6
1990	2.4	0.3
2005	0.4	+
2009	0.2	+
2010	0.2	+
2011	0.4	0.1
2012	0.3	0.1
2013	0.3	0.1

+ Does not exceed 0.05 kt.

In 2013, U.S. primary aluminum production totaled approximately 1.9 million metric tons, a 6 percent decrease from 2012 production levels (USAA 2014). In 2013, five companies managed production at ten operational primary aluminum smelters. Three smelters were closed temporarily for the entire year in 2013 (USGS 2014). During 2013, monthly U.S. primary aluminum production was lower for every month in 2013, when compared to the corresponding months in 2012 (USAA 2014).

For 2014, total production was approximately 1.7 million metric tons compared to 1.9 million metric tons in 2013, a 12 percent decrease (USAA 2014). Based on the decrease in production, process CO_2 and PFC emissions are likely to be lower in 2014 compared to 2013 if there are no significant changes in process controls at operational facilities.

Methodology

Process CO_2 and perfluorocarbon (PFC)—i.e., perfluoromethane (CF_4) and perfluoroethane (C_2F_6)—emission estimates from primary aluminum production for 2010 through 2013 are available from EPA's GHGRP—Subpart F (Aluminum Production) (EPA 2014). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2013) 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, carbon dioxide (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 (and certain technology-specific defaults) detailed in subpart F (aluminum production).[179] 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.

Process CO_2 Emissions from Anode Consumption and Anode Baking

CO_2 emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated with IPCC (2006) 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 C 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 C 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 C 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 (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.

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[179] *See* Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. Available online at: <www.epa.gov/ghgreporting/documents/pdf/infosheets/aluminumproduction.pdf>.

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

Smelter-specific PFC emissions from aluminum production for 2010 through 2013 were reported to EPA under its GHGRP. To estimate their PFC emissions 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:

$$\text{PFC } (CF_4 \text{ or } C_2F_6) \text{ kg/metric ton Al} = S \times (\text{Anode Effect Minutes/Cell-Day})$$

where,

S = Slope coefficient ((kg PFC/metric ton Al)/(Anode Effect Minutes/Cell-Day))
Anode Effect Minutes/Cell-Day = (Anode Effect Frequency/Cell-Day) × Anode Effect Duration (minutes)

They then multiply this emission factor by aluminum production to estimate PFC emissions. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

PFC 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 or USAA, 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.

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 the difference between reporting smelters and national aluminum production levels (from USGS and USAA), with allocation to specific smelters based on reported production capacities (from USGS).

National primary aluminum production data for 2013 were obtained via The Aluminum Association (USAA 2014). For 1990 through 2001, and 2006 (see Table 4-79) data were obtained from USGS Mineral Industry Surveys: Aluminum Annual Report (USGS 1995, 1998, 2000, 2001, 2002, 2007). For 2002 through 2005, and 2007 through 2011, national aluminum production data were obtained from the USAA's Primary Aluminum Statistics (USAA 2004–2006, 2008–2013).

Table 4-79: Production of Primary Aluminum (kt)

Year	kt
1990	4,048
2005	2,478
2009	1,727
2010	1,727
2011	1,986
2012	2,070
2013	1,948

Uncertainty and Time Series Consistency

Uncertainty was assigned to the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP. As previously mentioned, the methods for estimating emissions for EPA's GHGRP and this report are the same, and follow the IPCC (2006) methodology. As a result, it was possible to assign uncertainty bounds (and distributions) based on an analysis of the uncertainty associated with the facility-specific emissions estimated for previous Inventory years. 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 ±6, ±16, and ±20 percent, respectively. 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 4-80. Aluminum production-related CO_2 emissions were estimated to be between 3.2 and 3.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below to 2 percent above the emission estimate of 3.3 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 2.2 and 2.4 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 6 percent below to 7 percent above the emission estimate of 2.3 MMT CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.6 and 0.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 11 percent below to 11 percent above the emission estimate of 0.7 MMT CO_2 Eq.

Table 4-80: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	3.3	3.2	3.3	−2%	+2%
Aluminum Production	CF_4	2.3	2.2	2.4	−6%	+7%
Aluminum Production	C_2F_6	0.7	0.6	0.7	−11%	+11%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

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 Aluminum Production 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

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous Inventory reports) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from PFCs. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

As a result, emission estimates for each year from 1990 to 2012 increased by 14 percent for CF_4, and increased by 33 percent for C_2F_6, relative to the emission estimates in the previous Inventory report.

Planned Improvements

Future improvements involve plans to replace proxy (e.g., interpolated) data with additional historical VAIP data that recently became available in order to calculate more accurate PFC emission estimates for the historical time series.

4.19 Magnesium Production and Processing (IPCC 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. Sulfur hexafluoride has been used in this application around the world for more than thirty years. A dilute gaseous mixture of SF_6 with dry air and/or 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. 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 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.

The magnesium industry emitted 1.4 MMT CO_2 Eq. (0.06 kt) of SF_6, 0.08 MMT CO_2 Eq. (0.06 kt) of HFC-134a, and 0.002 MMT CO_2 Eq. (2.1 kt) of CO_2, in 2013. This represents a decrease of approximately 8 percent from total 2012 emissions (see Table 4-81). The decrease can be attributed to reduction in primary, secondary, and die casting SF_6 emissions between 2012 and 2013 as reported through EPA's GHGRP, with the largest absolute reduction being seen for secondary emissions. The reduction in SF_6 emissions is likely due in part to decreased production from reporting facilities in 2013. The decrease in SF_6 emissions can also be attributed by continuing industry efforts to utilize SF_6 alternatives, such as HFC-134a, Novec™612 and SO_2, to reduce greenhouse gas emissions. In 2013, total HFC-134a emissions increased from 0.01 MMT CO_2 Eq. to 0.08 MMT CO_2 Eq., while the FK 5-1-12 emissions were constant. The emissions of carrier gas, CO_2, also decreased from 2.3 kt in 2012 to 2.1 kt in 2013.

Table 4-81: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
SF_6	5.2	2.7	1.6	2.1	2.8	1.6	1.4
HFC-134a	0.0	0.0	+	+	+	+	0.1
CO_2	+	+	+	+	+	+	+
FK 5-1-12	*0.0*	*0.0*	+	+	+	+	+
Total[a]	**5.2**	**2.8**	**1.7**	**2.1**	**2.8**	**1.7**	**1.5**

Note: Emission values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.
[a] Total does not include FK 5-1-12. Values shown for informational purposes only.

Table 4-82: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (kt)

Year	1990		2005		2009	2010	2011	2012	2013
SF_6	0.2		0.1		0.1	0.1	0.1	0.1	0.1
HFC-134a	0.0		0.0		+	+	+	+	0.1
CO_2	1.4		2.9		1.2	1.3	3.1	2.3	2.1
FK 5-1-12	*0.0*		*0.0*		+	+	+	+	+

+ Does not exceed 0.5 kt

Methodology

Emission estimates for the magnesium industry incorporate information provided by some 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 the 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 was assumed to be equivalent to emissions. Along with SF_6, some Partners also reported their HFC-134a and FK 5-1-12 usage, which is assumed to be equal to emissions. 2010 was the last reporting year under the Partnership. Emissions data for 2011 through 2013 were 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, 1999 through 2010, and 2011 through 2013. The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS).

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.

SF_6 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. Emission factor for die casting of 4.1 kg SF_6 per metric ton was available for the mid-1990s from an international survey (Gjestland & Magers 1996) that 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 is reported in the RAND survey of major SF_6 manufacturers, which shows 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. 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 4-81. These 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 is then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year. The emissions of carrier gases for permanent mold, wrought and anode processes are not estimated in this Inventory.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production are 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.

The die casting emission estimates for 1999 through 2010 are 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 and from 2008 through 2010, Partners did not account for all die casting tracked by USGS, and, therefore, it was necessary to estimate the emissions of die casters who were not Partners. 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. For 2008 through 2010, the characteristics of the die casters who were not Partners were not well known, and therefore the emission factor for these die casters was set equal to 3.0 kg SF_6 per metric ton of magnesium, the average of the emission factors reported over the same period by the die casters who were Partners.

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 1999-2001, the sand casting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sand casting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to all other sand casters.

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 4-83.

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.

CO_2 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 total quantity of all cover gases used (SF_6, HFC-134a, and FK5-1-12) by production type in this time period. 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. The emissions of carrier gases for permanent mold, wrought and anode processes are not estimated in this Inventory.

Table 4-83: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	2.14[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	0.10	2	1	1
2009	2.30	2	1	1
2010	2.94	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000-2007), Partners made up 100 percent of die casters in the U.S.

[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 2013

For 2011 through 2013, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For die and sand casting, some emissions data was obtained through EPA's GHGRP. The balance of the emissions for these industry segments were 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. 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. 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. For 2013, pre-published USGS consumption statistics were obtained via communications with USGS (USGS 2013)

Uncertainty and Time Series Consistency

Uncertainty surrounding the total estimated emissions in 2013 is attributed to the uncertainties around SF_6, HFC-134a and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2013 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 2013 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2013 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 reporting program, 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. Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP program. One known sand caster (the lone Partner) has not reported since 2007 and its activity and emission factor were held constant at 2005 levels due to a reporting anomaly in 2006 because of malfunctions at the facility. The uncertainty associated with the SF_6 usage for the sand casting Partner was 85 percent. 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 4-84). 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 uncertainties 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 4-84. Total emissions associated with magnesium production and processing 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 11 percent below to 12 percent above the 2013 emission estimate of 1.5 MMT CO_2 Eq. The uncertainty estimates for 2013 are similar relative to the uncertainty reported for 2012 in the previous Inventory report.

Table 4-84: 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	2013 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	1.5	1.3	1.7	-11%	+12%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

In the current Inventory, emission estimates for alternate cover gases and carrier gas has been incorporated as the information is now available from EPA's GHGRP. The alternative cover gases have lower GWPs than SF_6, and tend to quickly degrade during their exposure to the molten metal. Magnesium producers and processors began using these cover gases starting in around 2006, as based on Partnership reported data. The amounts being used by companies on the whole are low and have a minor effect on the overall emissions from the industry. This is also attributable to their relatively lower GWPs. SF_6 has a GWP of 22,800, whereas HFC-134a has a GWP of 1,430. Similarly, EPA's GHGRP now provides access to data on carrier gases, allowing for this information to be integrated in the Inventory. Emissions of CO_2 have also been included in the total emissions from the industry. This has led to slight increase in overall emissions for each year compared to the previous Inventory. CO_2 carrier gas emissions have been included across the entire time series to ensure time series consistency.

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for SF_6. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

As a net result, emission estimates for each year from 1990 to 2013 have slightly decreased, relative to the previous Inventory report.

For one facility, a recalculation for 2011 SF_6 emissions was performed to ensure methodological consistency. The emissions for this facility and year were previously estimated using a company-specific growth rate based on data reported through the Partnership. This estimate has been revised by interpolating the reported emissions between 2010 and 2012, reported via the Partnership and EPA's GHGRP respectively. This has caused a slight increase in the SF_6 emissions for 2011 compared to the previous Inventory.

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.

Usage and emission details of carrier gases in permanent mold, wrought and anode processes will be researched as part of a future inventory. Based on this research, it will be determined if CO_2 carrier gas emissions are to be estimated.

4.20 Lead Production (IPCC Source Category 2C5)

Lead production in the United States consists of both primary and secondary processes—both of which emit CO_2 (Sjardin 2003). Emissions from fuels consumed for energy purposes during the production of lead are accounted for in 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, occurs at a just a single smelter in Missouri. This primary lead smelter was closed at the end of 2013 (USGS 2014b).

Similar to primary lead production, CO_2 emissions from secondary 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. Of all the domestic secondary smelters operational in 2013, 12 smelters had capacities of 30,000 tons or more and were collectively responsible for more than 95 percent of secondary lead production in 2013 (USGS 2014a). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2013, secondary lead production accounted for nearly 90 percent of total lead production. Similarly, secondary lead accounted for approximately 68 percent of total domestic lead consumption (USGS 2014a).

In 2013, total secondary lead production in the United States was slightly less than that in 2012. Domestic secondary lead producers expanded capacity and others closed plants, but total production capacity remained essentially unchanged. In April 2013, a leading producer closed its 70,000 ton capacity smelter in Reading, PA, and in September reduced production at its 90,000 ton capacity smelter in Vernon, CA, by 15 percent. Increases in exports of spent lead-acid batteries in recent years have decreased the amount of scrap available to secondary smelters (USGS 2014a).

U.S. primary lead production increased by approximately 6 percent from 2012 to 2013, and has decreased by 71 percent since 1990. In 2013, U.S. secondary lead production slightly decreased from 2012 levels by approximately 1 percent, but has increased by 19 percent since 1990 (USGS 1995 through 2013, USGS 2014a).

In 2013, U.S. primary and secondary lead production totaled 1,218,000 metric tons (USGS 2014a). The resulting emissions of CO_2 from 2013 lead production were estimated to be 0.5 MMT CO_2 Eq. (525 kt) (see Table 4-85). The majority of 2013 lead production is from secondary processes, which accounted for 94 percent of total 2013 CO_2 emissions from lead production. At last reporting, the United States was the third largest mine producer of lead in the world, behind China and Australia, accounting for approximately 6 percent of world production in 2013 (USGS 2014a).

Table 4-85: CO_2 Emissions from Lead Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.5	516
2005	0.6	553
2009	0.5	525
2010	0.5	542
2011	0.5	538
2012	0.5	527
2013	0.5	525

After a steady increase in total emissions from 1995 to 2000, total emissions have gradually decreased since 2000 but were still 2 percent greater in 2013 than in 1990. Although primary production has decreased significantly (71 percent since 1990), secondary production has increased by about 19 percent over the same time period. Since secondary production is more emissions-intensive, the increase in secondary production since 1990 has resulted in a net increase in emissions despite the sharp decrease in primary production (USGS 1995 through 2013; USGS 2014a).

Methodology

The methods used to estimate emissions for lead production are based on Sjardin's work (Sjardin 2003) for lead production emissions and Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation is as follows:

$$CO_2\ Emissions = (DS \times EFa) + (S \times EFb)$$

Where,

DS = Lead produced by direct smelting, metric ton
S = Lead produced from secondary materials
EFa, b = Applicable emission factor, metric tons CO_2/metric ton product

For primary lead production using direct smelting, Sjardin (2003) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) 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 1990 through 2013 activity data for primary and secondary lead production (see Table 4-86) were obtained from the USGS (USGS 1995 through 2013; 2014a).

Table 4-86: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000

2005	143,000	1,150,000
2009	103,000	1,110,000
2010	115,000	1,140,000
2011	118,000	1,130,000
2012	111,000	1,110,000
2013	118,000	1,100,000

Uncertainty and Time-Series Consistency

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. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-87. Lead production CO_2 emissions were estimated to be between 0.4 and 0.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below and 15 percent above the emission estimate of 0.5 MMT CO_2 Eq.

Table 4-87: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	0.5	0.4	0.6	-14%	+15%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements involve evaluating and analyzing data reported under EPA's GHGRP to improve the emission estimates for the Lead Production source category. Particular attention would be made to ensure time series consistency of the emission 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.[180]

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[180] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

4.21 Zinc Production (IPCC Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy CO_2 emissions (Viklund-White 2000). Emissions from fuels consumed for energy purposes during the production of zinc are accounted for in 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, copper ingot manufacturing, etc.). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Primary production in the United States is conducted through the electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other metallurgical, hydrometallurgical, and pyrometallurgical processes. Worldwide primary zinc production also employs a pyrometallurgical process using the Imperial Smelting Furnace process; 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.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 2)}$$

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 1100-1200°C, 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 ton of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

The only companies in the United States that use emissive technology to produce secondary zinc products are Horsehead, PIZO, and Steel Dust Recycling. For Horsehead, EAF dust is recycled in Waelz kilns at their Beaumont, TX; Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. These Waelz kiln facilities produce intermediate zinc products (crude zinc oxide or calcine), most of which is transported to their Monaca, PA facility where the products are smelted into refined zinc using electrothermic technology. Some of Horsehead's intermediate zinc products that are not smelted at Monaca are instead exported to other countries around the world (Horsehead 2010a). PIZO and Steel Dust Recycling recycle EAF dust into intermediate zinc products using Waelz kilns, and then sell the intermediate products to companies who smelt it into refined products.

In 2013, U.S. primary and secondary refined zinc production were estimated to total 250,000 metric tons (USGS 2014b) (see Table 4-88). Domestic zinc mine production increased slightly in 2013 compared to 2012 levels, primarily owing to increase in zinc production at a zinc-lead mine in Alaska and two zinc-mining complexes in Tennessee. Zinc metal production decreased by 4 percent owing to a decline in secondary production; a zinc-recycling company closed its smelter in Pennsylvania towards the end of 2013 as it began production at its new recycling facility in North Carolina starting 2014 (USGS 2014b). Primary zinc production (primary slab zinc) increased slightly in 2013, while, secondary zinc production in 2013 decreased relative to 2012.

Emissions of CO_2 from zinc production in 2013 were estimated to be 1.4 MMT CO_2 Eq. (1,429 kt) (see Table 4-89). All 2013 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the

U.S. have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2013, emissions were estimated to be 126 percent higher than they were in 1990.

Table 4-88: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	95,708
2005	191,120	156,000
2009	94,000	109,000
2010	120,000	129,000
2011	110,000	138,000
2012	114,000	147,000
2013	120,000	130,000

Table 4-89: CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.6	632
2005	1.0	1,030
2009	0.9	943
2010	1.2	1,182
2011	1.3	1,286
2012	1.5	1,486
2013	1.4	1,429

Methodology

The methods used to estimate non-energy CO_2 emissions from zinc production using the electrothermic primary production and Waelz kiln secondary production processes are based on Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from 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.

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:

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

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:

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

The total amount of EAF dust consumed by Horsehead at their Waelz kilns was available from Horsehead financial reports for years 2006 through 2013 (Horsehead 2007, 2008, 2010a, 2011, 2012, 2013, and 2014). Consumption levels for 1990 through 2005 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States as provided by *USGS Minerals Yearbook: Zinc* (USGS 1995 through 2006). 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 Horsehead's Waelz kiln facilities.

The amount of EAF dust consumed by Steel Dust Recycling (SDR) and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2013 (Rowland 2012 and 2014). SDR's facility in Alabama underwent expansion in 2011 to include a second unit (operational since early- to mid-2012). SDR's facility has been operational since 2008. Annual consumption data for SDR was not publicly available for the years 2008, 2009, and 2010. These data were estimated using data for Horsehead's Waelz kilns for 2008-2010 (Horsehead 2007, 2008, 2010a, 2010b, and 2011). Annual capacity utilization ratios were calculated using Horsehead's annual consumption and total capacity for the years 2008-2010. Horsehead'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 (Steel Dust Recycling LLC 2013).

PIZO Technologies Worldwide LLC's facility in Arkansas has been operational since 2009. The amount of EAF dust consumed by PIZO's facility for 2009 through 2013 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of Horsehead'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 2013 were estimated by applying the average annual capacity utilization rates for Horsehead and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012, 2013, and 2014; Rowland 2012 and 2014; PIZO 2012 and 2014). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's and Steel Dust Recycling's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

Refined zinc production levels for Horsehead's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). Production levels for 1990 through 2004 were extrapolated using the percentage changes in annual refined zinc production at secondary smelters in the United States as provided by USGS Minerals Yearbook: Zinc (USGS 1995 through 2005). The 3.70 metric tons CO_2/metric ton zinc emission factor was then applied to the Monaca facility's production levels to estimate CO_2 emissions for the facility. The Waelz kiln production emission factor was applied in this case rather than the EAF dust consumption emission factor since Horsehead's Monaca facility did not consume EAF dust.

Uncertainty and Time-Series Consistency

The uncertainties contained in these estimates are two-fold, relating to activity data and emission factors used.

First, 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 (1) an EAF dust consumption value reported annually by Horsehead Corporation as part of its financial reporting to the Securities and Exchange Commission (SEC), and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated in Alabama by Steel Dust Recycling LLC. Since actual EAF dust consumption information is not available for PIZO's facility (2009-2010) and SDR's facility (2008-2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's Web site) by the capacity utilization factor for Horsehead Corporation (which is available from Horsehead's financial reports). Also, the EAF dust consumption for PIZO's facility for 2011-2013 was estimated by multiplying the average capacity utilization factor developed from Horsehead Corp. 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 and SDR's annual EAF dust consumption values (except SDR's EAF dust consumption for 2011-2013 which were obtained from SDR's recycling facility in Alabama).

Second, there are uncertainties 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 depend 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. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-90. Zinc production CO_2 emissions were estimated to be between 1.2 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 18 percent above the emission estimate of 1.4 MMT CO_2 Eq.

Table 4-90: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Zinc Production	CO_2	1.4	1.2	1.7	-16%	+18%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

In the previous version of the Inventory (i.e., 1990-2012), EAF dust consumption data for SDR's Alabama facility were not available for 2012. Therefore, 2011 data were used as proxy for 2012. During 2013 updates to the Inventory, these data were obtained from SDR (Rowland 2014). This change caused an increase of approximately 4.5 percent in the 2012 emissions.

Planned Improvements

Future improvements involve evaluating and analyzing data reported under EPA's GHGRP to improve the emission estimates for the Zinc Production source category. Particular attention would 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, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[181]

4.22 Semiconductor Manufacture (IPCC Source Category 2E1)

The semiconductor industry uses multiple long-lived fluorinated greenhouse gases in plasma etching and plasma enhanced chemical vapor deposition (PECVD) processes to produce semiconductor products. The gases most commonly employed are trifluoromethane (HFC-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6),

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[181] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and nitrous oxide (N_2O), although other 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.

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. 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 generated and emitted as a process by-product. 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).

For 2013, total CO_2 weighted emissions of all fluorinated greenhouse gases and nitrous oxide by the U.S. semiconductor industry were estimated to be 4.2 MMT CO_2 Eq. Combined emissions of all greenhouse gases are presented in Table 4-91 and Table 4-92 below for years 1990, 2005 and the period 2009 to 2013. The rapid growth of this industry and the increasing complexity (growing number of layers[182]) of semiconductor products led to an increase in emissions of 153 percent between 1990 and 1999, when emissions peaked at 9.1 MMT CO_2 Eq. The emissions growth rate began to slow after 1999, and emissions declined by 54 percent between 1999 and 2013. Together, industrial growth, adoption of emissions reduction technologies, including but not limited to abatement technologies, and shift in gas usages resulted in a net increase in emissions of 16 percent between 1990 and 2013.

There was a sizable dip seen in emissions between 2008 and 2009, a 28 percent decrease, due to the slowed economic growth, and hence production, during this time. The industry recovered and emissions rose between 2009 and 2010 by more than 25 percent and between 2010 and 2011 by 29 percent; reductions in emissions were observed between 2011 and 2012, and 2012 and 2013 at 9 percent and 7 percent, respectively.

Table 4-91: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (MMT CO_2 Eq.)

Year	1990	2005	2009	2010	2011	2012	2013
CF_4	0.8	1.1	0.8	1.1	1.4	1.3	1.2
C_2F_6	2.0	1.9	1.1	1.4	1.8	1.6	1.5
C_3F_8	+	0.1	0.1	0.1	0.2	0.1	0.1
C_4F_8	+	0.1	+	+	0.1	0.1	0.1
HFC-23	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SF_6	0.5	0.7	0.3	0.4	0.4	0.4	0.4
NF_3	+	0.5	0.4	0.5	0.7	0.6	0.6
Total F-GHGs	**3.6**	**4.6**	**2.9**	**3.7**	**4.7**	**4.3**	**4.0**
N_2O	+	0.1	0.1	0.1	0.2	0.2	0.2

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[182] 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.

Total	**3.6**	**4.7**	**3.1**	**3.8**	**4.9**	**4.5**	**4.2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-92: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (kt)

Year	1990	2005	2009	2010	2011	2012	2013
CF_4	0.11	0.14	0.11	0.14	0.19	0.17	0.16
C_2F_6	0.16	0.16	0.09	0.11	0.14	0.13	0.12
C_3F_8	+	+	+	+	+	+	+
C_4F_8	+	+	+	+	+	+	+
HFC-23	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
N_2O	0.12	0.41	0.45	0.49	0.79	0.65	0.61

+ Does not exceed 0.05 kt

Methodology

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, Partner reported emissions data received through the EPA's PFC[183] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions in the absence of emission control strategies (Burton and Beizaie 2001)[184], and estimates of industry activity (i.e., total manufactured layer area). The availability and applicability of reported data from the EPA Partnership and EPA's GHGRP differs across the 1990 through 2013 time series. Consequently, F-GHG emissions from semiconductor manufacturing were estimated using five distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, and 2011 through 2013. N_2O emissions were estimated using three distinct methods, one each for the period 1990 through 1994, 1995 through 2010, and 2011 through 2013.

1990 through 1994

From 1990 through 1994, Partnership data were unavailable and emissions were modeled using the PEVM (Burton and Beizaie 2001).[185] 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 layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

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[183] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[184] 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. For 2011, while no MOU existed, it was assumed that the same companies that were Partners in 2010 were "Partners" in 2011 for purposes of estimating inventory emissions.

[185] 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.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[186] and (2) product type (discrete, memory or logic).[187] 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. The emission factor is used to estimate world uncontrolled emissions using publicly-available data on world 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).

To estimate N_2O emissions, it is assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through1994.

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 (Semiconductor Equipment and Materials Industry 2012 and 2013). Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period, the N_2O emissions were estimated using an emission factor that is 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 the GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2013 section. The total U.S. TMLA manufactured were estimated using PEVM.

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[186] 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).

[187] 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.

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 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 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.[188] Gas-specific emissions from non-Partners were estimated using linear interpolation of gas-specific emission distribution of 1999 (assumed same as total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partner facilities from GHGRP reported emissions data). 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 fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[189,190,191]

The N_2O emissions were estimated using the same methodology as 1995-1999 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

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[188] 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.

[189] 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 2–3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFW 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.

[190] 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.

[191] 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.

therefore greater numbers of layers.[192] 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 actual utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. 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.

The N_2O emissions were estimated using the same methodology as 1995 through 1999 methodology.

2011 through 2013

The fifth and final method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2013, the years after EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under the GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 mt CO_2 Eq. per year (based on default emission factors and total capacity in terms of substrate area) are required to report their emissions to the 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. In EPA's GHGRP, the population of non-Partner facilities also included manufacturers that use GaAs technology in addition to Si technology[193]. 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 populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of fluorinated GHGs used in etch and clean processes and as heat transfer fluids. They also report N_2O emissions from CVD and other processes. The fluorinated 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.

For the segment of the semiconductor industry, which 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 fluorinated GHGs and N_2O. The new emission factors (in units of mass of CO_2 Eq. / TMLA [MSI]) are based on the emissions reported by facilities under EPA's GHGRP and TMLA estimates for these facilities from the WFF (SEMI 2012 and SEMI 2013). In a refinement of the method used in prior years to estimate emissions for the non-Partner population, different emission factors were developed for different subpopulations of fabs, one for facilities that manufacture devices on Si wafers and one for facilities that manufacture on GaAs wafers. An analysis of the emission factors of reporting fabs showed that the characteristics that had the largest impacts on emission factors were the substrate (i.e., Si or GaAs) used at the fab, whether the fab contained R&D activities, and whether the fab reported using point-of-use fluorinated greenhouse gas abatement[194]. 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 fluorinated GHGs (CF_4, C_2F_6, C_3F_8, C_4F_8, CHF_3, SF_6 and NF_3)[195] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA)

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[192] 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.

[193] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[194] For the non-reporting segment of the industry using GaAs technology, emissions were estimated only for those fabs that manufactured the same products as manufactured by reporters. The products manufactured were categorized as discrete (emissions did not scale up with decreasing feature size).

[195] Only seven gases were aggregated because inclusion of fluorinated GHGs that are not reported in the inventory results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

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. To estimate emissions from fabs that are solely doing research and development (R&D) or are Pilot fabs (i.e., fabs that are excluded from subpart I reporting requirements), emission factors were estimated based on GHGRP reporting fabs containing R&D activities. EPA applied a scaling factor of 1.15 to the slope of the RTO model to estimate the emission factor applicable to the non-reporting fabs that are only R&D or Pilot fabs. This was done as R&D activities lead to use of more F-GHGs and N_2O for development of chips that are not counted towards the final estimated TMLA. Hence, it is assumed that the fabs with only R&D activities use 15 percent more F-GHGs and N_2O per TMLA. However, as was assumed for 2007 through 2010, fabs with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. Other fabs were assumed to utilize 89 percent of their manufacturing capacity, held constant at 2012 levels which is slightly lower than 2011 levels. Fabs that produce discrete products are assumed to utilize 84 percent of their manufacturing capacity, held constant at 2011 levels. These utilizations at 2011 levels are based on the Semiconductor Industry Association report (SICAS, 2011).

Non-reporting fabs were then broken out into similar subpopulations. Information on the technology and R&D activities of non-reporting fabs was available through the WFF. 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. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the GWP-weighted emissions of that subpopulation.

Gas-specific, GWP-weighted emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions from which the aggregate emission factors were developed. Estimated in this manner, the non-reporting population accounted for 9, 10 and 10 percent of U.S. emissions in 2011, 2012 and 2013, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

The methodology used for this time period included, for the first time, emissions from facilities employing Si- and GaAs-using technologies. The use of GaAs technology became evident via analysis of GHGRP emissions and WFF data. However, no adjustment of pre-2011 emissions was made because (1) the use of these technologies appears relatively new, (2) in the aggregate make a relatively small contribution to total industry emissions (i.e., 4 percent in 2013), and (3) would require a large effort to retroactively adjust pre-2011 emissions.

Data Sources

GHGRP reporters estimated their emissions using a default emission factor method established by EPA. This method is very similar to the Tier 2b Method in the *2006 IPCC Guidelines*, but it goes beyond that method by establishing different default emission and by-product generation factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes (in situ thermal, in situ thermal, and remote plasma). Partners estimated their emissions using a range of methods. 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*. 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 2013) (e.g., Semiconductor Materials and Equipment Industry, 2013). Actual worldwide capacity utilizations for 2011 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA, 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.

Uncertainty and Time-Series Consistency

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 equation used to estimate uncertainty is:

$$\text{Total Emissions } (E_T) = \text{GHGRP Reported F-GHG Emissions } (E_{R,F\text{-}GHG}) + \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,F\text{-}GHG}) + \text{GHGRP Reported } N_2O \text{ Emissions } (E_{R,N_2O}) + \text{Non-Reporters' Estimated } N_2O \text{ Emissions } (E_{NR,N_2O})$$

where E_R and E_{NR} denote totals for the indicated subcategories of emissions for F-GHG and N_2O, respectively.

The uncertainty in E_T presented in Table 4-93 below results from the convolution of four distributions of emissions, each reflecting separate estimates of possible values of $E_{R,F\text{-}GHG}$, E_{R,N_2O}, $E_{NR,F\text{-}GHG}$, and E_{NR,N_2O}. The approach and methods for estimating each distribution and combining them to arrive at the reported 95 percent CI are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG}$, or GHGRP reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment were developed during the assessment of emission estimation methods for the subpart I GHGRP 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).[196] The 2012 analysis did not take into account the use of abatement. For the industry segment that processed 200 mm wafers, estimates of uncertainties 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 the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. These gas and wafer-specific uncertainty estimates are applied to the total emissions of the facilities that did not abate emissions as reported under EPA's GHGRP.

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 0 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 of the gases area abated (i.e., the maximum value) and that 50 percent is the most likely value and the minimum is 0 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 Montel Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG}$ 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 ($E_{R,F\text{-}GHG}$).

The uncertainty in $E_{R,N2O}$ 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

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[196] 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.

distribution with a minimum value of 0 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 of the facilities reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,F\text{-}GHG}$ and $E_{NR,N2O}$ entailed developing estimates of uncertainties for the emissions factors for each non-reporting sub-category 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. For production fabs the most probable utilization is assumed to be 89 percent, with the highest and lowest utilization assumed to be 100 percent and 63 percent, respectively. The corresponding values for facilities that manufacture discrete devices are, 84 percent, 100 percent, and 66 percent, respectively, while the values for utilization for R&D facilities, are assumed to be 20 percent, 33 percent, and 9 percent, respectively. The most probable utilizations are unchanged compared to 2012 Inventory year. To address the uncertainty in the capacity utilization for Inventory year 2013, the lower bound has been decreased by 10 percent, and the upper bound has been increased by 10 percent (or 100 percent if greater than 100 percent) compared to the bounds used in the 2012 Inventory year. 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 each non-reporting category of facilities is dependent on the uncertainty of the total emissions (MMT CO_2 Eq. units) and the TMLA of each reporting facility in that category. For each subpopulation of reporting facilities, total emissions were regressed on TMLA (with an intercept forced to zero) for 10,000 emissions and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5th and the 97.5th percentile of these emission factors are determined and the bounds are assigned as the percent difference from the estimated emission factor.

For simplicity, the results of the Monte Carlo simulations on the bounds of the gas- and wafer size-specific emissions as well as the TMLA and emission factors are assumed to be normally distributed and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The departures from normality were observed to be small.

The final step in estimating the uncertainty in emissions of non-reporting facilities is convolving the distribution of emission factors with the distribution of TMLA using Monte Carlo simulation.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-93, which is also obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility. The emissions estimate for total U.S. F-GHG and N_2O emissions from semiconductor manufacturing were estimated to be between 4.0 and 4.4 MMT CO_2 Eq. at a 95 percent confidence level. This range represents 5 percent below to 5 percent above the 2013 emission estimate of 4.2 MMT CO_2 Eq. 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 4-93: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Semiconductor Manufacture (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Semiconductor Manufacture	HFC, PFC, SF_6, NF_3, and N_2O	4.2	4.0	4.4	-5%	5%

[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.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in emissions from CH_4, HFCs, PFCs, SF_6, and NF_3. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

The decrease in the GWP of SF_6 and increase in the GWP of all other gases had several impacts on Inventory estimates. In the 1990 through 1994 time period, an overall increase in total annual GWP-weighted emissions is seen. In the 1995 through 2010 time period, the Inventory methodology relies on various gas distributions based on Partner reported emissions and PEVM estimated emissions. The changes in GWP carry through to changes in the estimated gas distributions, and hence changes in gas-by-gas emission estimates, in CO_2 Eq., and total annual fluorinated greenhouse gas emission estimates, in CO_2 Eq..

For the first time, NF_3 and N_2O have been included in total annual GWP-weighted emission estimates for the United States. This, along with an increased weighted GWP from SAR to AR4 led to increase in total emissions for all years as compared to previous Inventories. The emissions of each gas were impacted by the increase in overall emissions as well as the percent distribution of each gas as a result of changes in their GWPs.

Emissions in years 2011 and 2012 were updated to reflect updated emissions reporting in EPA's GHGRP. For the non-reporting population, the methodology to determine the non-reporting population for GaAs using facilities has been updated. In the updated methodology, revised assumptions were made about the GaAs using facilities that use fluorinated greenhouse gases (e.g., only the non-reporters that use wafers greater than or equal to four inches have been assumed to use fluorinated greenhouse gases, facilities that use wafers less than 4 inches are assumed to use wet etching and hence do not consume or emit any fluorinated greenhouse gases). Further, EPA has drawn an analogy between GaAs-using GHGRP reporters and non-reporters provided the non-reporters use wafers greater than 4 inches and manufacture the many versions of high electron mobility transistors (HEMT, PHEMT, MHEMT, HET, MOFETs), which are discrete devices and may be made to specific order by certain foundries. By virtue of this analogy, EPA has estimated emissions only from the non-reporters that use GaAs technology and manufacture HEMT and their variations. While other devices may be made using GaAs technology, EPA has no reporters under the GHGRP that manufacture them and hence has no basis for estimating an emission factor. EPA has thus assumed that they do not use or emit F-GHGs. This has decreased the non-reporting facilities subpopulation, and subsequently total emissions for the years 2011 and 2012.

Planned Improvements

This Inventory contains estimates of seven fluorinated gases for semiconductor manufacturing. However, other fluorinated gases (e.g., C_5F_8) are used in relatively smaller, but significant amounts. Previously, emissions data for these other fluorinated gases was not reported through the EPA Partnership. Through EPA's GHGRP, these data, as well as heat transfer fluid emission data, are available. Therefore, a point of consideration for future Inventory reports is the inclusion of other fluorinated gases, and emissions from heat transfer fluid (HTF) loss to the atmosphere.

Fluorinated heat transfer fluids, of which some are liquid perfluorinated compounds, are used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Evaporation of these fluids is a source of fluorinated emissions (EPA 2006). The GHGRP-reported HTF emissions along with WFF database could be used to develop emission factors for identified subpopulations. Further research needs to be done to determine if the same subpopulations identified in developing new emission factors for F-GHGs are applicable or new subpopulations have to be studied as HTFs are used primarily by manufacturers of wafer size 300 mm and above.

Along with more emissions information for semiconductor manufacturing, EPA’s GHGRP requires the reporting of emissions from other types of electronics manufacturing, including micro-electro-mechanical systems, flat panel displays, and photovoltaic cells. There currently are no flat panel displays, and photovoltaic cell manufacturing facilities that are reporting to EPA’s GHGRP, and five reporting MEMs manufacturers. The MEMs manufacturers also report emissions from semiconductor manufacturing and do not distinguish between these two types of manufacturing in their report; thus, emissions from MEMs manufacturers are included in the totals here. Emissions from manufacturing of flat panel displays and photovoltaic cells may be included in future Inventory reports; however, estimation methodologies would need to be developed.

4.23 Substitution of Ozone Depleting Substances (IPCC Source Category 2F)

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[197] 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. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 4-94 and Table 4-95.

Table 4-94: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2009	2010	2011	2012	2013
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	1.8	2.6	3.3	4.3	5.2
HFC-125	+	11.0	22.0	28.1	33.7	40.0	46.3
HFC-134a	+	81.9	87.9	86.5	81.4	76.5	71.3
HFC-143a	+	10.7	15.5	17.9	20.3	22.8	25.3
HFC-236fa	0.0	1.2	1.4	1.4	1.4	1.5	1.5
CF_4	0.0	+	+	+	+	+	+
Others*	0.3	5.9	7.4	7.8	8.2	8.6	9.0
Total	**0.3**	**111.1**	**136.0**	**144.4**	**148.4**	**153.5**	**158.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

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[197] [42 U.S.C § 7671, CAA Title VI]

* Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, 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 C_6F_{14}.
Note: Totals may not sum due to independent rounding.

Table 4-95: Emissions of HFCs and PFCs from ODS Substitution (MT)

Gas	1990	2005	2009	2010	2011	2012	2013
HFC-23	+	1	2	2	2	2	2
HFC-32	+	505	2,611	3,849	4,925	6,309	7,733
HFC-125	+	3,147	6,290	8,038	9,615	11,415	13,236
HFC-134a	+	57,286	61,467	60,509	56,929	53,478	49,837
HFC-143a	+	2,401	3,460	3,996	4,547	5,091	5,651
HFC-236fa	+	125	144	146	147	148	151
CF_4	+	2	3	3	4	4	4
Others*	M	M	M	M	M	M	M

M (Mixture of Gases)
+ Does not exceed 0.5 MT
* Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

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—and HFC-134a in refrigeration end-uses. 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.[198] 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.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 158.6 MMT CO_2 Eq. in 2013. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Table 4-96 presents emissions of HFCs and PFCs as ODS substitutes by end-use sector for 1990 through 2013. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2013 include refrigeration and air-conditioning (137.6 MMT CO_2 Eq., or approximately 87 percent), aerosols (10.5 MMT CO_2 Eq., or approximately 7 percent), and foams (7.4 MMT CO_2 Eq., or approximately 5 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (44.1 MMT CO_2 Eq.), followed by refrigerated retail food and refrigerated transport. Each of the end-use sectors is described in more detail below.

Table 4-96: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990	2005	2009	2010	2011	2012	2013
Refrigeration/Air Conditioning	+	99.2	119.7	126.0	129.0	133.3	137.6
Aerosols	0.3	7.6	9.4	9.7	10.1	10.3	10.5
Foams	+	2.1	4.2	5.9	6.4	6.9	7.4
Solvents	+	1.7	1.6	1.7	1.7	1.7	1.8
Fire Protection	+	0.7	1.0	1.1	1.2	1.3	1.3
Total	**0.3**	**111.1**	**136.0**	**144.4**	**148.4**	**153.5**	**158.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

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[198] R-404A contains HFC-125, HFC-143a, and HFC-134a.

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, and metallurgical industries). As the ODS phaseout is taking effect, most equipment is being or will eventually be retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[199] R-404A, and R-507A.[200] These HFCs are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal events.

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). Many 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 has started to use HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to “not-in-kind” technologies, such as solid roll-on deodorants and finger-pump sprays. The transition away from ODS 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. These propellants are released into the atmosphere as the aerosol products are used.

Foams

CFCs 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, methylene chloride, 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 polyurethane 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. 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

CFCs, 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

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[199] R-410A contains HFC-32 and HFC-125.

[200] R-507A, also called R-507, contains HFC-125 and HFC-143a.

require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of 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 sale of 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. As fire protection equipment is tested or deployed, emissions of these HFCs occur.

Methodology

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 and PFCs. 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 60 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.

Uncertainty and Time-Series Consistency

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 Vintaging Model estimates emissions from 60 end-uses. The uncertainty analysis, however, quantifies the level of uncertainty associated with the aggregate emissions resulting from the top 21 end-uses, comprising over 95 percent of the total emissions, and 6 other end-uses. These 27 end-uses comprise 97 percent of the total emissions, equivalent to 153.3 MMT CO_2 Eq. In an effort to improve the uncertainty analysis, additional end-uses are added annually, with the intention that over time uncertainty for all emissions from the Vintaging Model will be fully characterized. Any end-uses included in previous years' uncertainty analysis were included in the current uncertainty analysis, whether or not those end-uses were included in the top 95 percent of emissions from ODS Substitutes.

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 for the current year or original ODS consumption. Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed. The most significant sources of uncertainty for this source category include the emission factors for residential unitary AC, as well as the percent of non-MDI aerosol propellant that is HFC-152a.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-97. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 153.0 and 172.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 0.22 percent below to 12.4 percent above the emission estimate of 158.6 MMT CO_2 Eq.

Table 4-97: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2013 Emission Estimate (MMT CO_2 Eq.)[a]	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	158.6	153.0	172.3	-0.22%	+12.4%

[a] 2013 emission estimates and the uncertainty range presented in this table correspond to selected end-uses within the aerosols, foams, solvents, fire extinguishing agents, and refrigerants sectors that comprise 97 percent of total emissions, but not for other remaining categories. Therefore, because the uncertainty associated with emissions from "other" ODS substitutes was not estimated, they were excluded in the uncertainty estimates reported in this table.

[b] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from HFCs and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

The decrease in the GWP of HFC-152a and increase in the GWP of all other gases had several impacts on Inventory estimates. In the 1990 through 1991 time period, an overall decrease in total annual GWP-weighted emissions is seen. After 1991, there is an overall increase in total emissions.

In addition, a review of the MVACs, streaming agents, window AC units, ice makers, and small retail food end-uses resulted in revisions to the Vintaging Model since the previous Inventory. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013.

For the MVAC light-duty vehicle (LDV) and light-duty trucks (LDT) end-uses, operational and servicing leak rates were reduced based on a review of recent literature. For the small retail food and ice makers end-uses, revisions were made to the overall stock, growth rates, assumed transition scenarios, and lifetimes based on research on substitutes and growth in the market. For window air-conditioning, a review of air conditioner sales data from 2002 through 2012 increased the quantity of window air-conditioning equipment introduced into the market for 2002 and 2004 through 2008, while decreasing the quantity of equipment sold into the market for 2003 and 2009 through 2012. In the streaming agents end-use, the assumed transition scenarios were revised based on industry input. Combined, these assumption changes and the use of AR4 GWPs increased GHG emissions on average by 7 percent across the time series.

4.24 Electrical Transmission and Distribution (IPCC 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.

Fugitive emissions of SF_6 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 from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 5.1 MMT CO_2 Eq. (0.2 kt) in 2013. This quantity represents an 80 percent decrease from the estimate for 1990 (see Table 4-98 and Table 4-99). There are two potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the magnitude and 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. Utilities participating in the Partnership have lowered their emission factor (kg SF_6 emitted per kg of nameplate capacity) by more than 75 percent since the Partnership began in 1999. A recent examination of the SF_6 emissions reported by electric power systems to EPA's GHGRP revealed that SF_6 emissions from reporters has decreased by 25 percent from 2011 to 2013, 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 (Ottinger et al. 2014).

Table 4-98: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	25.1	0.3	25.4
2005	9.8	0.8	10.6
2009	6.7	0.6	7.3
2010	6.2	0.9	7.0
2011	5.7	1.1	6.8
2012	4.6	1.1	5.7
2013	4.2	0.9	5.1

Notes: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding.

Table 4-99: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

Year	Emissions
1990	1.1
2005	0.5
2009	0.3
2010	0.3
2011	0.3
2012	0.2

2013	0.2

Methodology

The estimates of emissions from Electrical Transmission and Distribution 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 in1999, 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 to 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales were 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* (IPCC 2006).[201] (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.)

$$\text{Emissions (kilograms } SF_6\text{)} = SF_6 \text{ purchased to refill existing equipment (kilograms)} + \text{nameplate capacity of retiring equipment (kilograms)}$$ [202]

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 14.3 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

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[201] Ideally, sales to utilities in the U.S. 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.

[202] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

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 2013 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2013 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 the EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); and (3) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, and 2013 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013), which was applied to the electric power systems that do not report to EPA (Non-Reporters). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

Partners

Over the period from 1999 to 2013, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership, represented between 42 percent and 48 percent 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 2013, approximately 0.3 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 91 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP. Partners without verified 2013 data accounted for approximately 9 percent of the total emissions attributed to Partner utilities.[203]

GHGRP-Only 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. Many Partners began reporting their emissions through EPA's GHGRP in 2012 (reporting emissions for 2011 and later years) because their nameplate capacity exceeded the reporting threshold. Partners who did not report through EPA's GHGRP continued to report through the Partnership.

In addition, many non-Partners began reporting to EPA for the first time through its GHGRP in 2012. Non-Partner emissions reported and verified under EPA's GHGRP were compiled to form a new category of reported data

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[203] It should be noted that data reported through the GHGRP must go through a verification process; only data verified as of September 1, 2014 could be used in the emission estimates for 2013. For Partners whose GHGRP data was not yet verified, emissions were extrapolated based upon historical Partner-specific transmission mile growth rates, and those Partners are included in the 'non-reporting Partners' category.

For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted. In addition, EPA manually reviewed the reported data and compared each facility's reported transmission miles with the corresponding quantity in the UDI 2013 database (UDI 2013). In the first year of GHGRP reporting, EPA followed up with reporters where the discrepancy between the reported miles and the miles published by UDI was greater than 10 percent, with a goal to improve data quality. Only GHGRP data verified as of September 1, 2014 was included in the emission estimates for 2011, 2012, and 2013.

(GHGRP-Only Reporters). GHGRP-Only Reporters accounted for 24 percent of U.S. transmission miles and 26 percent of estimated U.S. emissions from electric power system in 2013.[204]

Non-Reporters

Emissions from Non-Reporters (i.e., utilities other than Partners and GHGRP-Only Reporters) in every year since 1999 were estimated using the results of a regression analysis that correlated emissions from reporting utilities (using verified data from both Partners and GHGRP-Only Reporters) with their transmission miles.[205] Two equations were developed, one for "non-large" and one for "large" utilities (i.e., with fewer or greater than 10,000 transmission miles, respectively). The distinction between utility sizes was made because the regression analysis showed that the relationship between emissions and transmission miles differed for non-large and large transmission networks. As noted above, non-Partner emissions were reported to the EPA for the first time through its GHGRP in 2012 (representing 2011 emissions). This set of reported data was of particular interest because it provided insight into the emission rate of non-Partners, which previously was assumed to be equal to the historical (1999) emission rate of Partners for both large and non-large utilities.[206] The availability of non-Partner emissions estimates allowed the regression analysis to be modified for both large and non-large groups. Specifically, emissions were estimated for Non-Reporters as follows:

- <u>Non-Reporters, 1999 to 2011:</u> First, the 2011 emission rates (per kg nameplate capacity and per transmission mile) reported by Partners and GHGRP-Only Reporters were reviewed to determine whether there was a statistically significant difference between these two groups. Transmission mileage data for 2011 was reported through GHGRP, with the exception of transmission mileage data for Partners that did not report through GHGRP, which was obtained from UDI. It was determined that there is no statistically significant difference between the emission rates of Partners and GHGRP-Only reporters; therefore, Partner and GHGRP-Only reported data for 2011 were combined to develop regression equations to estimate the emissions of Non-Reporters for both "non-large" and "large" utilities. Historical emissions from Non-Reporters for both "non-large" and "large" utilities were estimated by linearly interpolating between the 1999 regression coefficients (based on 1999 Partner data) and the 2011 regression coefficients.

- <u>Non-Reporters, 2012 - Present:</u> It was determined that there continued to be no statistically significant difference between the emission rates reported by Partners and by GHGRP-Only Reporters. Therefore, the emissions data from both groups were combined to develop regression equations for 2012. This was repeated for 2013 using Partner and GHGRP-Only Reporter data for 2013.

    - *"Non-large" utilities (less than 10,000 transmission miles):* The 2013 regression equation for "non-large" utilities was developed based on the emissions reported by a subset of 89 Partner utilities and GHGRP-Only utilities (representing approximately 47 percent of total U.S. transmission miles for utilities with fewer than 10,000 transmission miles). The regression equation for 2013 is:

$$\text{Emissions (kg)} = 0.217 \times \text{Transmission Miles}$$

    - *"Large" utilities (more than 10,000 transmission miles)*: The 2013 regression equation was developed based on the emissions reported by a subset of 17 Partners and GHGRP-only utilities (representing approximately 83 percent of total U.S. transmission miles for utilities with greater than 10,000 transmission miles). The regression equation for 2013 is:

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[204] Also, GHGRP-reported emissions from 17 facilities that had one or fewer transmission miles were included in the emission estimates for 2011. Emissions from these facilities comprise approximately 1.2 percent of total reported and verified emissions. In 2012, 16 facilities had one or fewer transmission miles, comprising 1.4 percent of verified emissions and in 2013, 16 facilities had one or fewer transmission miles, comprising 3.2 percent of verified emissions. These facilities were not included in the development of the regression equations (discussed further below). EPA is continuing to investigate whether or not these emissions are already implicitly accounted for in the relationship between transmission miles and emissions, and whether to update the regression analysis to better capture emissions from non-reporters that may have zero transmission miles.

[205] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

[206] Partners in EPA's SF_6 Emission Reduction Partnership reduced their emissions by approximately 77 percent from 1999 to 2013.

Emissions (kg) = 0.225 × Transmission Miles

Table 4-4-100 below shows the percentage of transmission miles covered by reporters (i.e., associated with reported data) and the regression coefficient for both large and non-large reporters for 1999 (the first year data was reported), and for 2011 through 2013 (the first three years with GHGRP reported data). The coefficients for non-large utilities and large utilities both decreased slightly between 2012 and 2013.

Table 4-4-100: Transmission Mile Coverage and Regression Coefficients for Large and Non-Large Utilities, Percent

	Non-large				Large			
	1999	2011	2012	2013	1999	2011	2012	2013
Percentage of Miles Covered by Reporters	31	45	44	47	86	97	88	83
Regression Coefficient[a]	0.89	0.33	0.23	0.22	0.58	0.27	0.24	0.22

[a] Regression coefficient is defined as emissions (in kg) divided by transmission miles.

Note: “Non-large” represents reporters with fewer than 10,000 transmission miles.

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, and 2012 were obtained from the 2001, 2004, 2007, 2010, and 2013 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013). The U.S. transmission system grew by over 25,000 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. This growth rate grew to 3 percent from 2006 to 2009 as transmission miles increased by more than 59,000 miles. The annual growth rate for 2009 through 2012 was calculated to be 2.0 percent as transmission miles grew by approximately 43,000 during this time period.

Total Industry Emissions

As a final step, total electric power system emissions from 1999 through 2013 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, and the non-reporting utilities’ emissions (determined using the regression equations).

1990 through 2013 Emissions from Manufacture of Electrical Equipment

The 1990 to 2013 emission estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 provided with new equipment. 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; the quantities of SF_6 provided with new equipment for 2001 to 2013 were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (198.2 MMT CO_2 Eq. in 2013). 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 2013 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. 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).

Uncertainty and Time-Series Consistency

To estimate the uncertainty associated with emissions of SF_6 from Electrical Transmission and Distribution, 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 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 2.5 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 20 percent.[207] Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 5.8 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2013 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) the quantity of SF_6 supplied with equipment by equipment manufacturers, which is projected from Partner provided nameplate capacity data and industry SF_6 nameplate capacity estimates, and (2) the manufacturers' SF_6 emissions rate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-101. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 4.0 and 6.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 20 percent below and 19 percent above the emission estimate of 5.1 MMT CO_2 Eq.

Table 4-101: Approach 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2013 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	5.1	4.0	6.0	-20%	+19%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

In addition to the uncertainty quantified above, there is 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.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

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[207] Uncertainty is assumed to be higher for the GHGRP-Only category, because 2011 is the first year that those utilities have reported to EPA.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2 Eq. emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2 Eq. emissions for SF_6. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Only taking this change into consideration, emissions estimates for each year from 1990 to 2012 would have slightly decreased, relative to the emissions estimates in the previous Inventory report. However, other changes to the historical calculations, as noted below, resulted in emission estimates fluctuating slightly (increasing for some years and decreasing for other years) across the time series.

The historical emissions estimated for this source category have undergone several minor revisions. SF_6 emission estimates for the period 1990 through 2012 were updated relative to the previous report based on revisions to interpolated and extrapolated non-reported Partner data as well as resubmissions of estimates through the GHGRP for 2011 and 2012.[208] The previously-described interpolation between 1999 and 2012 regression coefficients to estimate emissions from non-reporting utilities were updated using revised GHGRP reports, which impacted historical estimates for the period 2000 through 2012. Additionally, updated leak rates were calculated from resubmitted Partner data through the GHGRP. These leak rates are used to estimate the nameplate capacity of non-reporters during these years, and are interpolated back through 1999 to calculate Non-Reporter nameplate capacity over the entire time series.[209] Finally, revisions were made regarding the incorporation of transmission mile data from the UDI database to remove instances of double counting transmission miles between parent and subsidiary companies. Reductions in the total transmission miles reduced the total number of non-reporter transmission miles, which reduced non-reporter emissions, and therefore total emissions.

As a result of the recalculations, SF_6 emissions from electrical transmission and distribution decreased by 6 percent for 2012 relative to the previous report. On average, the change in SF_6 emission estimates for the entire time series is approximately 0.5 percent per year.

Planned Improvements

EPA is exploring the use of OEM data that is reported under EPA's GHGRP to use for future Inventory reports instead of estimating those emissions based on elements reported by utilities to the GHGRP and Partner data. Specifically, using the GHGRP-reported OEM emissions and the estimated nameplate capacity increase estimated for users of electrical equipment (available in the existing methodology), a leak rate would be calculated. This approach would require estimating the portion of industry not reporting to the GHGRP program, which would require market research. Once a new leak rate is established, leak rates could be interpolated for years between 2000 (at 10 percent) and 2011. 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.[210]

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[208] The earlier year estimates within the time series (i.e., 1990-1998) were updated based on revisions to the 1999 U.S. emission estimate because emissions for 1990-1998 are estimated by multiplying a series of annual factors by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (see Methodology section).

[209] Nameplate capacity estimates affect sector emissions because OEM emission estimation is calculated using total industry nameplate capacity.

[210] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

Box 4-2: Potential Emission Estimates of HFCs, PFCs, SF_6, and NF_3

Emissions of HFCs, PFCs, SF_6, and NF_3 from industrial processes can be estimated in two ways, either as potential emissions or as actual emissions. Emission estimates in this chapter are "actual emissions," which are defined by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) as estimates that take into account the time lag between consumption and emissions. In contrast, "potential emissions" are defined to be equal to the amount of a chemical consumed in a country, minus the amount of a chemical recovered for destruction or export in the year of consideration. Potential emissions will generally be greater for a given year than actual emissions, since some amount of chemical consumed will be stored in products or equipment and will not be emitted to the atmosphere until a later date, if ever. Although actual emissions are considered to be the more accurate estimation approach for a single year, estimates of potential emissions are provided for informational purposes.

Separate estimates of potential emissions were not made for industrial processes that fall into the following categories:

- *By-product emissions*. Some emissions do not result from the consumption or use of a chemical, but are the unintended by-products of a process. For such emissions, which include emissions of CF_4 and C_2F_6 from aluminum production and of HFC-23 from HCFC-22 production, the distinction between potential and actual emissions is not relevant.
- *Potential emissions that equal actual emissions*. For some sources, such as magnesium production and processing, no delay between consumption and emission is assumed and, consequently, no destruction of the chemical takes place. In this case, actual emissions equal potential emissions.

Table 4-102 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances, HFCs, PFCs, SF_6, and NF_3 from semiconductor manufacture, and SF_6 from magnesium production and processing and electrical transmission and distribution.[211] Potential emissions associated with the substitution for ozone depleting substances were calculated using the EPA's Vintaging Model. Estimates of HFCs, PFCs, and SF_6 consumed by semiconductor manufacture were developed by dividing chemical-by-chemical emissions by the appropriate chemical-specific emission factors from the *2006 IPCC Guidelines* (Tier 2c). Estimates of CF_4 consumption were adjusted to account for the conversion of other chemicals into CF_4 during the semiconductor manufacturing process, again using the default factors from the *2006 IPCC Guidelines*. Potential SF_6 emissions estimates for electrical transmission and distribution were developed using U.S. utility purchases of SF_6 for electrical equipment. From 1999 through 2013, estimates were obtained from reports submitted by participants in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems as well as EPA's Greenhouse Gas Reporting Program (GHGRP). U.S. utility purchases of SF_6 for electrical equipment from 1990 through 1998 were backcasted based on world sales of SF_6 to utilities. Purchases of SF_6 by utilities were added to SF_6 purchases by electrical equipment manufacturers to obtain total SF_6 purchases by the electrical equipment sector.

Table 4-102: 2013 Potential and Actual Emissions of HFCs, PFCs, SF_6, and NF_3 from Selected Sources (MMT CO_2 Eq.)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	306.9	158.6
Aluminum Production	NA	3.0
HCFC-22 Production	NA	4.1
Semiconductor Manufacture	43.7	4.0
Magnesium Production and Processing	1.5	1.5
Electrical Transmission and Distribution	33.3	5.1

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
NA - Not applicable.

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[211] See Annex 5 for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

Under EPA's GHGRP, producers and larger importers and exporters[212] of fluorinated greenhouse gases (F-GHG) in bulk began annually reporting their production, destruction, imports, and exports in 2011 (for 2010 supplies), and larger importers and exporters of F-GHGs inside of pre-charged equipment began reporting their imports and exports in 2012 (for 2011 supplies). The collection of data from both emitters and suppliers of F-GHGs enables the comparison of consumption that is implied by emissions (downstream estimation method) to the consumption that is implied by balancing of production, destruction, imports, and exports (upstream estimation method). This type of comparison ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines*:

> "[W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic consumption as calculated in this 'potential emissions approach' per compound with the sum of all activity data of the various uses (IPCC 2006)."

A comparison of upstream and downstream consumption estimates of SF_6 was performed to help evaluate the accuracy and completeness of the emissions inventory. This analysis revealed that the two potential emissions estimates for 2012 (the upstream estimation and downstream estimation methods) differed with the supply-based, upstream consumption estimate significantly larger than emitter-based, downstream consumption estimate (Ottinger et al. 2014). This finding indicates that methods for determining national SF_6 actual emission estimates by industry sector are generating results that, when summed, do not fall within a close proximity to the overall total U.S. supply of SF_6 gas.

While multiple sources of uncertainty affect both data sets, Ottinger et al (2014) conclude that current SF_6 emission estimates likely do not account for all significant sources of SF_6 in the United States. Additional research is necessary to identify the other significant applications that consume and emit SF_6.

4.25 Nitrous Oxide from Product Uses (IPCC Source Category 2G3)

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. 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 2014). N_2O 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).

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[212] Importers and exporters report only if either their total imports or their total exports of F-GHGs are greater than or equal to 25,000 metric tons of CO_2 Eq. per year

Production of N_2O in 2013 was approximately 15 kt (Table 4-103).

Table 4-103: N_2O Production (kt)

Year	kt
1990	16
2005	15
2009	15
2010	15
2011	15
2012	15
2013	15

N_2O emissions were 4.2 MMT CO_2 Eq. (14 kt) in 2013 (Table 4-104). 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 4-104: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	4.2	14
2005	4.2	14
2009	4.2	14
2010	4.2	14
2011	4.2	14
2012	4.2	14
2013	4.2	14

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Methodology

Emissions from N_2O product uses were estimated using the following equation:

$$E_{pu} = \sum_{a} (P \times S_a \times ER_a)$$

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 (i.e., anesthesia, food processing, etc.). In 2013, the medical/dental industry used an estimated 86.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other categories combined used the remainder of the N_2O produced. This subcategory breakdown has changed only slightly over the past decade. For instance, the small share of N_2O usage in the production of sodium azide has 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). The N_2O was allocated across the following categories: medical applications, food processing propellant, and sodium azide production (pre-1996). A usage emissions rate was then applied for each sector to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were estimated to release emissions into the atmosphere, and therefore these subcategories were the only usage subcategories with emission rates. 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/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 report (Heydorn 1997). N_2O 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 (2003) 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 (2003) 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 2003). 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 unavailability of data, production estimates for years 2004 through 2013 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 report (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 2001share 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 unavailability of data, the share of total quantity of N_2O usage data for years 2004 through 2013 was assumed to equal the 2003 value. The emissions rate for the food processing propellant industry was obtained from SRI Consulting's Nitrous Oxide, North America report (Heydorn 1997), and confirmed by a N_2O industry expert (Tupman 2002). The emissions rate for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with the 2013 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* (2006) 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 results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-105. N_2O emissions from N_2O product usage were estimated to be between 3.2 and 5.2 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 4.2 MMT CO_2 Eq.

Table 4-105: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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 Product Use	N_2O	4.2	3.2	5.2	-24%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Furthermore, methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Planned Improvements

Planned improvements include a continued evaluation of alternative production statistics for cross verification, a reassessment of N_2O product use subcategories to accurately represent trends, investigation of 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.

Future Inventories 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 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.

4.26 Industrial Processes and Product Use Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various ozone precursors (i.e., indirect greenhouse gases). As some of industrial applications also employ thermal incineration as a control technology, combustion by-products, such as carbon monoxide (CO) and nitrogen oxides (NO_x), are also reported with this source category. Non-CH_4 volatile organic compounds (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. Accidental releases of greenhouse gases 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 small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in this chapter.

Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from non-energy industrial processes and product use from 1990 to 2013 are reported in Table 4-106.

Table 4-106: NO_x, CO, and NMVOC Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
NO_x	**653**	**631**	**544**	**521**	**498**	**498**	**498**
Industrial Processes							
Other Industrial Processes	378	482	395	374	353	353	353
Metals Processing	97	66	76	73	71	71	71
Chemical and Allied Product Manufacturing	168	61	54	53	51	51	51
Storage and Transport	3	16	13	16	20	20	20
Miscellaneous[a]	6	2	2	2	3	3	3
Product Use							
Surface Coating	1	3	3	2	1	1	1
Graphic Arts	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Other Industrial Processes[b]	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
CO	**4,552**	**1,716**	**1,467**	**1,411**	**1,355**	**1,355**	**1,355**
Industrial Processes							
Metals Processing	2,640	829	815	791	766	766	766
Other Industrial Processes	537	534	397	367	337	337	337
Chemical and Allied Product Manufacturing	1,183	208	178	173	167	167	167
Miscellaneous[a]	111	36	51	53	56	56	56
Storage and Transport	76	107	21	24	27	27	27
Product Use							
Surface Coating	1	2	5	3	2	2	2
Other Industrial Processes[b]	4	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0
Graphic Arts	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
NMVOCs	**8,419**	**6,448**	**4,781**	**4,556**	**4,331**	**4,331**	**4,331**
Industrial Processes							
Storage and Transport	1,490	1,442	1,143	1,093	1,043	1,043	1,043
Other Industrial Processes	401	457	351	340	329	329	329
Chemical and Allied Product Manufacturing	634	235	86	85	83	83	83
Metals Processing	122	49	36	35	34	34	34
Miscellaneous[a]	22	19	28	29	30	30	30
Product Use							
Surface Coating	2,523	1,739	1,285	1,218	1,152	1,152	1,152
Non-Industrial Processes[c]	1,900	1,594	1,177	1,116	1,055	1,055	1,055
Degreasing	744	309	228	217	205	205	205
Dry Cleaning	215	254	187	178	168	168	168

Graphic Arts	274	213	158	149	141	141	141
Other Industrial Processes[b]	94	97	71	68	64	64	64
Other	0	39	29	28	26	26	26

[a] Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, cooling towers, 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.

[b] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[c] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2013 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Data were collected for emissions of carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOC), and sulfur dioxide (SO_2) from metals processing, chemical manufacturing, other industrial processes, transport and storage, and miscellaneous sources. Emission estimates for 2013 for non-EGU and non-mobile sources are held constant from 2011 in EPA (2015). Emissions were calculated either for individual source categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed or the amount of solvent purchased) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Emissions for product use were calculated by aggregating product use data based on information relating to product uses from different applications such as degreasing, graphic arts, etc. Emission factors for each consumption category were then applied to the data to estimate emissions. For example, emissions from surface coatings were mostly due to solvent evaporation as the coatings solidify. By applying the appropriate product-specific emission factors to the amount of products used for surface coatings, an estimate of NMVOC emissions was obtained. Emissions of CO and NO_x under product use result primarily from thermal and catalytic incineration of solvent-laden gas streams from painting booths, printing operations, and oven exhaust.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA’s Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty and Time-Series Consistency

Uncertainties in these estimates are partly due to the accuracy of the emission factors and activity data used. A quantitative uncertainty analysis was not performed.

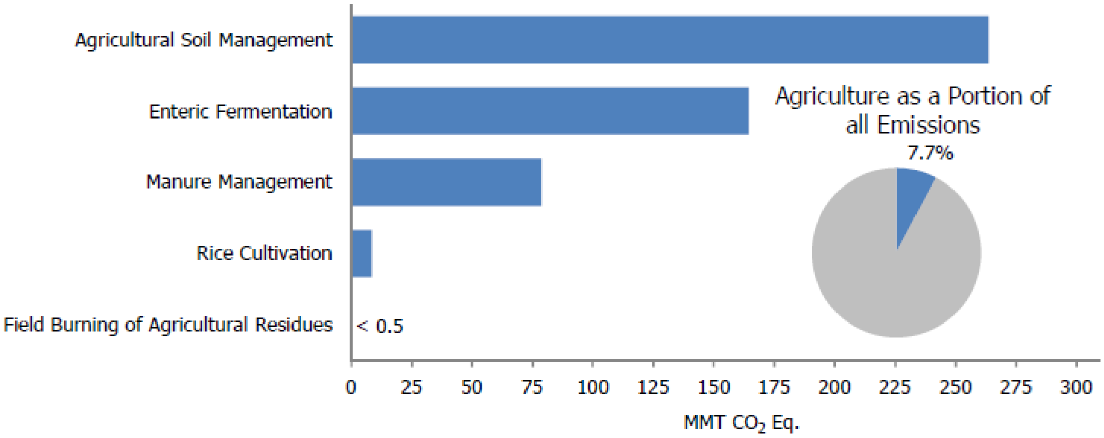
Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon-dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 5-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as liming of agricultural soils and conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry chapter. Carbon dioxide emissions from on-farm energy use are accounted for in the Energy chapter.

Figure 5-1: 2013 Agriculture Chapter Greenhouse Gas Emission Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



In 2013, the Agriculture sector was responsible for emissions of 515.7 MMT CO_2 Eq.,[1] or 7.7 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent 25.9 percent and 9.6 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 74.2 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

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[1] Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2013, CH_4 emissions from agricultural activities increased by 11.3 percent, while N_2O emissions fluctuated from year to year, but overall increased by 18.2 percent.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CH_4	**210.8**	**234.4**	**242.1**	**243.4**	**238.9**	**239.6**	**234.5**
Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5
Manure Management	37.2	56.3	59.7	60.9	61.4	63.7	61.4
Rice Cultivation	9.2	8.9	9.4	11.1	8.5	9.3	8.3
Field Burning of Agricultural Residues	0.3	0.2	0.3	0.3	0.3	0.3	0.3
N_2O	**237.9**	**260.1**	**281.2**	**281.4**	**283.2**	**283.4**	**281.1**
Agricultural Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7
Manure Management	13.8	16.4	17.0	17.1	17.3	17.3	17.3
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**448.7**	**494.5**	**523.3**	**524.8**	**522.1**	**523.0**	**515.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CH_4	**8,431**	**9,375**	**9,685**	**9,736**	**9,558**	**9,585**	**9,381**
Enteric Fermentation	6,566	6,755	6,908	6,844	6,750	6,653	6,581
Manure Management	1,486	2,254	2,388	2,437	2,457	2,548	2,456
Rice Cultivation	366	358	378	444	339	372	332
Field Burning of Agricultural Residues	13	9	12	11	12	12	12
N_2O	**798**	**873**	**944**	**944**	**950**	**951**	**943**
Agricultural Soil Management	752	817	886	887	892	892	885
Manure Management	46	55	57	57	58	58	58
Field Burning of Agricultural Residues	+	+	+	+	+	+	+

+ Less than 0.5 kt.
Note: Totals may not sum due to independent rounding.

5.1 Enteric Fermentation (IPCC 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.

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 2013 were 164.5 MMT CO_2 Eq. (6,581 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2013. Emissions from dairy cattle in 2013 accounted for 25 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.

From 1990 to 2013, emissions from enteric fermentation have increased by 0.2 percent. While emissions generally follow trends in cattle populations, over the long term there are exceptions as population decreases have been coupled with production increases or minor decreases. For example, beef cattle emissions decreased 1.7 percent from 1990 to 2013, while beef cattle populations actually declined by 7 percent and beef production increased 13 percent (USDA 2014), and while dairy emissions increased 5.7 percent over the entire time series, the population has declined by 5 percent and milk production increased 36 percent (USDA 2014). This trend indicates that while emission factors per head are increasing, emission factors per unit of product are going down. Generally, from 1990 to 1995 emissions from beef 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. Emissions generally increased from 2005 to 2007, as both dairy and beef populations underwent increases and an extensive literature review and analysis of more than 350 dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Total emissions decreased again from 2008 to 2013 as beef cattle populations again decreased. Regarding trends in other animals, during the timeframe of this analysis, populations of sheep have decreased 53 percent while horse populations have increased 60 percent, with each annual increase ranging from about 2 to 9 percent between 1990 and 2007, followed by a 2 percent annual decline through 2013. Goat populations increased by about 25 percent through 2007 but have since dropped back to 1990 numbers, while swine populations have increased 22 percent during this timeframe. The population of American bison more than tripled, while mules and asses have more than doubled.

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2009	2010	2011	2012	2013
Beef Cattle	119.1	125.2	125.5	124.4	121.7	118.7	117.1
Dairy Cattle	39.4	37.6	41.0	40.7	41.1	41.7	41.6
Swine	2.0	2.3	2.5	2.4	2.5	2.5	2.5
Horses	1.0	1.7	1.7	1.7	1.7	1.6	1.6
Sheep	2.3	1.2	1.1	1.1	1.1	1.1	1.1
Goats	0.3	0.4	0.4	0.4	0.3	0.3	0.3
American Bison	0.1	0.4	0.4	0.4	0.3	0.3	0.3
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**164.2**	**168.9**	**172.7**	**171.1**	**168.7**	**166.3**	**164.5**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	2005	2009	2010	2011	2012	2013
Beef Cattle	4,763	5,007	5,022	4,976	4,867	4,747	4,684
Dairy Cattle	1,574	1,503	1,639	1,626	1,643	1,669	1,664
Swine	81	92	99	97	98	100	99
Horses	40	70	70	68	67	65	64

Sheep	91	49	46	45	44	43	43
Goats	13	14	15	14	14	13	13
American Bison	4	17	15	15	14	13	13
Mules and Asses	1	2	3	3	3	3	3
Total	**6,566**	**6,755**	**6,908**	**6,844**	**6,750**	**6,653**	**6,581**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock 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 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 handled using a less detailed approach (i.e., IPCC Tier 1).

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, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

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 2014).

Diet characteristics were estimated by region for dairy, foraging 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: 1990-1993, 1994-1998, 1999-2003, 2004-2006, 2007, and 2008 onward.[2] Base year Y_m values by region were estimated using Donovan (1999). 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. More details are provided in Annex 3.10.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2013. 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 sheep; swine; goats; horses; mules and asses; and American bison were obtained for available years from USDA NASS (USDA 2014). Horse, goat and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 1992, 1997, 2014); the remaining years between 1990 and 2013 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, and 2012 (USDA 2014) and from the National Bison Association (1999) for 1997 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). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For

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[2] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003, as well.

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).

See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty and Time-Series Consistency

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 report (i.e., 2003 submission to the UNFCCC). There have been no significant changes to the methodology since that time; consequently, these uncertainty estimates were directly applied to the 2013 emission estimates in this Inventory report.

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.

The uncertainty ranges associated with the activity data-related input variables were plus or minus 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 2013 were estimated to be between 146.4 and 194.1 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2013 emission estimate of 164.5 MMT CO_2 Eq. 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 previous uncertainty analysis because the Food and Agricultural Organization of the United Nations (FAO) 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 now from the same USDA source as the other animal types, 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.

Table 5-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	164.5	146.4	194.1	-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 2013 estimates.

[c] The overall uncertainty calculated in 2003, and applied to the 2013 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.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan. Tier 2 QA procedures included independent peer review of emission estimates. The recent addition of emission estimates from calves to the enteric fermentation model and further separation of calves in beef and dairy subcategories made this the area of emphasis for QA/QC this year, with specific attention to the data sources and comparisons of the current estimates with previous estimates.

In addition, 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 now utilizes the 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 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

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations Chapter. This resulted in no change in CH_4 emissions, but an increase of 19 percent in enteric emissions CO_2 equivalent.

There were no modifications to the methodology that had an effect on emission estimates, therefore the only recalculations were due to changes in activity data, including the following.

- Foraging animal types from 2007 through 2012 show minor revisions in emissions. The region designations for the post 2006 foraging diets were offset by one from the states from Montana-onward (alphabetically).
- There was a transcription error in the CEFM that, when corrected, resulted in slight changes to the emissions from feedlot cattle between 1992 and 2013. The overall impact is a slight decrease in enteric emissions from cattle.
- The USDA published minor revisions in several categories that affected historical emissions estimated for cattle in 2012, including dairy cow milk production for several states and beef cattle feedlot placement data. These changes had an insignificant impact on the overall results.
- The 2012 USDA Census of Agriculture was released, providing updated 2012 population estimates for horses, goats, American bison, and mules and asses. As a result, emissions between 2008 and 2012 increased an average of 11 percent, 10 percent, 1.4 percent, and 25 percent, respectively.

Planned Improvements

Continued research and regular updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. Future improvements for enteric fermentation could include some of the following options:

- Updating input variables that are from older data sources, such as beef births by month and beef cow lactation rates;

- Investigation of the availability of annual data for the DE and crude protein values of specific diet and feed components for foraging and feedlot animals;
- Further investigation on additional sources or methodologies for estimating DE for dairy, given the many challenges in characterizing dairy 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;
- 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;
- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses);
- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry; 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.

5.2 Manure Management (IPCC Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the N cycle through the nitrification and denitrification of the organic N in livestock dung and urine.[3] 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 to the groundwater below, in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

When livestock or poultry manure are 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 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 type, including the animal's digestive system, 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.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct

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[3] 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 (e.g., 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.

N_2O emissions to occur, the manure must first be handled aerobically where ammonia (NH_3) or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to dinitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). 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. 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 in 2013 were 61.4 MMT CO_2 Eq. (2,456 kt); in 1990, emissions were 37.2 MMT CO_2 Eq. (1,486 kt). This represents a 65 percent increase in emissions from 1990. Emissions increased on average by 1.1 MMT CO_2 Eq. (2.8 percent) annually over this period. The majority of this increase is due to swine and dairy cow manure, where emissions increased 48 and 115 percent, respectively. From 2012 to 2013, there was a 3.6 percent decrease in total CH_4 emissions, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

Although the majority 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 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. Although national dairy animal populations have generally been decreasing since 1990, some states have seen increases in their dairy 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 toward larger dairy and swine facilities 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 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, and 2007 farm-size distribution data reported in the *Census of Agriculture* (USDA 2014a).

In 2013, total N_2O emissions were estimated to be 17.3 MMT CO_2 Eq. (58 kt); in 1990, emissions were 13.8 MMT CO_2 Eq. (46 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 25 percent increase from 1990 to 2013 and a 0.1 percent decrease from 2012 through 2013. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted.

Table 5-6 and Table 5-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Animal Type	1990	2005	2009	2010	2011	2012	2013
CH_4[a]	**37.2**	**56.3**	**59.7**	**60.9**	**61.4**	**63.7**	**61.4**
Dairy Cattle	14.7	26.4	30.4	30.4	31.2	32.6	31.8
Beef Cattle	3.1	3.3	3.2	3.3	3.3	3.2	3.0
Swine	15.6	22.9	22.4	23.6	23.5	24.4	23.1
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Poultry	3.3	3.2	3.2	3.2	3.2	3.2	3.2
Horses	0.2	0.3	0.2	0.2	0.2	0.2	0.2

American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O^b	**13.8**	**16.4**	**17.0**	**17.1**	**17.3**	**17.3**	**17.3**
Dairy Cattle	5.1	5.4	5.6	5.6	5.7	5.8	5.7
Beef Cattle	5.9	7.2	7.5	7.5	7.7	7.6	7.6
Swine	1.2	1.7	1.9	1.9	1.9	1.9	1.9
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Goats	+	+	+	+	+	+	+
Poultry	1.4	1.6	1.5	1.5	1.5	1.6	1.6
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
American Bison	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+
Total	**51.0**	**72.8**	**76.7**	**78.0**	**78.7**	**81.0**	**78.8**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Less than 0.05 MMT CO_2 Eq.

[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.

Note: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

NA: Not available

Table 5-7: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2009	2010	2011	2012	2013
CH_4^a	**1,486**	**2,254**	**2,388**	**2,437**	**2,457**	**2,548**	**2,456**
Dairy Cattle	590	1,057	1,218	1,217	1,244	1,304	1,271
Beef Cattle	126	133	130	132	131	127	120
Swine	622	916	898	945	941	974	922
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	128	129	127	128	129
Horses	9	12	10	10	10	10	9
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O^b	**46**	**55**	**57**	**57**	**58**	**58**	**58**
Dairy Cattle	17	18	19	19	19	19	19
Beef Cattle	20	24	25	25	26	26	26
Swine	4	6	6	6	6	6	6
Sheep	+	1	1	1	1	1	1
Goats	+	+	+	+	+	+	+
Poultry	5	5	5	5	5	5	5
Horses	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA
Mules and Asses	+	+	+	+	+	+	+

+ Less than 0.5 kt.

[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.

Note: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N_2O emissions from managed systems.

NA: Not available

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. 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 methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of CH_4 emissions:

- 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;
- Volatile solids (VS) production rate (by animal type and state or United States);
- Methane producing potential (B_o) 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 2013 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from USDA National Agriculture Statistics Service (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, and 2012; horse and mule and ass population data for 1987, 1992, 1997, 2002 2007, and 2012; and American bison population for 2002, 2007 and 2012 were obtained from the *Census of Agriculture* (USDA 2014a). 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 used for cattle, please see Section 5.1.

- WMS usage was estimated for swine and dairy cattle for different farm size categories using data from USDA (USDA; APHIS 1996; Bush 1998; Ott 2000; USDA 2014a) and EPA (ERG 2000a; EPA 2002a; 2002b). 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). 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, 2008 and 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*. American bison VS production was assumed to be the same as NOF bulls.

- The maximum CH_4-producing capacity of the VS (B_o) 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 2006). 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 presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the AgSTAR project database (EPA 2012). 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) were multiplied by the maximum CH_4 producing capacity of the VS (B_o) (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.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect N_2O emissions:

- 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 volitalization ($EF_{volitalization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volitalization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

N_2O 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 rates 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, 2008 and ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex rates were assumed to be the same as NOF bulls.
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006). These data are appropriate because they were developed using U.S. data.
- 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 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) and American bison, the estimated amount of N excreted (kg per animal-year) 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).

Next, indirect N_2O emissions from volatilization (kg N_2O per year) were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{tas}$) divided by 100, and 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, and 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.

The direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year).

Uncertainty and Time-Series Consistency

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory report (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. A normal probability distribution was assumed for each source data category. 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. These uncertainty estimates were directly applied to the 2013 emission estimates as there have not been significant changes in the methodology since that time.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-8. Manure management CH_4 emissions in 2013 were estimated to be between 50.3 and 73.7 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2013 emission estimate of 61.4 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.5 and 21.5 MMT CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2013 emission estimate of 17.3 MMT CO_2 Eq.).

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	2013 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	61.4	50.3	73.7	-18%	+20%
Manure Management	N_2O	17.3	14.5	21.5	-16%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. 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. 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 and the sum of county estimates for the full time series.

Any updated data, including population, are validated by experts to ensure the changes are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_o, 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 2006 IPCC default values.

For additional verification, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default 2006 IPCC 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 default emission factors. The U.S. implied emission factors fall within the range of the 2006 IPCC default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are greater than the 2006 IPCC 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 and swine across the time series. This increase reflects the dairy 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.

Table 5-9: 2006 IPCC 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)	Implied CH_4 Emission Factors (kg/head/year)						
		1990	2005	2009	2010	2011	2012	2013
Dairy Cattle	48-112	30.2	59.4	65.6	66.6	67.5	70.2	68.8
Beef Cattle	1-2	1.5	1.6	1.6	1.6	1.7	1.7	1.6
Swine	10-45	11.5	15.0	13.6	14.6	14.3	14.7	14.0
Sheep	0.19-0.37	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Goats	0.13-0.26	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Poultry	0.02-1.4	52.0	44.7	43.6	45.4	46.5	48.9	51.2
Horses	1.56-3.13	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Mules and Asses	0.76-1.14	1.3	2.0	1.3	1.3	1.2	1.2	1.1
American Bison	NA	0.03	0.1	0.1	0.1	0.1	0.1	0.1

In addition, 2006 default IPCC 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

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each

greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations Chapter.

The CEFM produces population, VS and Nex data for cattle, excepting calves, that are used in the manure management inventory. As a result, all changes to the CEFM described in Section 5.1 contributed to changes in the population, VS and Nex data used for calculating CH_4 and N_2O cattle emissions from manure management. In addition, the manure management emission estimates included the following recalculations relative to the previous Inventory:

- Calves were reported separately as dairy and beef calves. In previous Inventories, all calves were included in the beef category. However, some calves are raised on dairy farms so the separation of calves into dairy and beef categories improves the accuracy of the emission estimates.
- State animal populations were updated to reflect updated USDA NASS datasets, which resulted in population changes for poultry and swine in 2012.
- Population changes also occurred for bison, goats, horses and mules and asses for 2008 through 2012 due to incorporation of new state-level census data.
- Temperatures changed across all years due to a systematic recalculation of temperature data by NOAA (Robel 2014). This caused a change in liquid system MCFs across all years and states, along with changes in certain years and states for non-liquid systems due to changing climate zones.

Planned Improvements

The uncertainty analysis will be updated in future Inventories to more accurately assess uncertainty of emission calculations. This update is necessary due to the extensive changes in emission calculation methodology, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N_2O emissions.

In the next Inventory report, updated AgSTAR anaerobic digester data will be incorporated. In addition, the 2012 Agricultural Census data will also be incorporated into the Inventory and will be used to update county-level animal population and WMS estimates.

5.3 Rice Cultivation (IPCC Source Category 3C)

Most of the world's rice, and all rice in the United States, is grown on flooded fields (Baicich 2013). When fields are flooded, aerobic decomposition of organic material gradually depletes most of the oxygen in the soil. Once depleted, soil conditions become anaerobic, and CH_4 is produced by the decomposition of soil organic matter by anaerobic methanogenic bacteria. Most of the CH_4 produced does not reach the atmosphere. Up to 60 to 90 percent is oxidized by aerobic methanotrophic bacteria in the soil (some oxygen remains at the interfaces of soil and water, and soil and root systems) (Holzapfel-Pschorn et al. 1985, Sass et al. 1990) and some is leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management systems used to cultivate rice are one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce much CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants die, thus blocking the primary CH_4 transport pathway to the atmosphere. The quantities of CH_4 released from deepwater fields are therefore believed to be significantly less than rice fields with shallower flooding depths (Sass 2001). Some flooded rice fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely due to soil aeration. Aeration not only causes existing soil CH_4 to oxidize, but also inhibits further CH_4 production in soils. In the United States, rice is grown under continuously flooded, shallow water conditions (USDA 2012) and mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (i.e., the use of urea and organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding, and weeding practices). Factors that influence the amount of organic material available for anaerobic decomposition (i.e., fertilizer use, soil type, rice variety,[4] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season. Soil temperature is an important factor regulating the activity of methanogenic bacteria which in turn affects the rate of CH_4 production. However, although temperature influences the time required to convert organic material to CH_4, the impact of soil temperature on CH_4 emissions is minor over the length of the growing season. The application of synthetic fertilizers also influences CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate and ammonium sulfate) appear to inhibit CH_4 formation. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States.

Rice is currently cultivated in seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas.[5] Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. Most rice farmers recycle crop residues from the previous rice or rotational crop, either by leaving them standing, disking them, or rolling them into fields. Most farmers also apply synthetic fertilizer (usually urea) to their fields. In addition, the climatic conditions of Arkansas, Florida, southwest Louisiana, and Texas often allow for a second, or ratoon, rice crop. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Ratoon crops are infrequent to non-existent in California, Mississippi, and Missouri. In 2012, Arkansas reported a larger-than-usual ratoon crop (10 percent) due to an early rice harvest followed by warm weather and heavy rains (ideal conditions for secondary growth and ratoon crops) (Hardke 2014). CH_4 emissions from ratoon crops are considerably higher than those from the primary crops due to the lack of a delay between cropping seasons (which would allow the stubble to decay aerobically) (Wang et al. 2013). Specifically, the amount of organic material available for anaerobic decomposition during ratoon crop production is considerably higher than the amount available with the first (i.e., primary) crop production.

Rice cultivation is a minor source of CH_4 emissions in the United States (see Table 5-10 and Table 5-11). In 2013, CH_4 emissions from rice cultivation were 8.3 MMT CO_2 Eq. (332 kt). Annual emissions have fluctuated unevenly between 1990 and 2013, ranging from an annual decrease of 24 percent from 2010 and 2011 to an annual increase of 18 percent from 2009 to 2010. There was an overall decrease of 16 percent between 1990 and 2006, due to an overall decrease in primary crop area. However, between 2006 and 2013 emission levels have increased by 8 percent due to increased ratooning and changes in production areas. California, Louisiana and Texas reported an increase in rice crop area from 2012 to 2013. All other states reported a decrease in rice crop area from 2012 to 2013. The factors that affect the rice acreage in any year vary from state to state and are typically the result of weather phenomena (Baldwin et al. 2010).

Table 5-10: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990	2005	2009	2010	2011	2012	2013
Primary	**6.7**	**8.0**	**7.3**	**8.6**	**6.2**	**6.3**	**5.8**
Arkansas	2.9	3.9	3.5	4.3	2.8	3.1	2.6
California	0.8	1.1	1.2	1.2	1.2	1.2	1.2
Florida	+	+	+	+	+	+	+
Louisiana	1.3	1.3	1.1	1.3	1.0	1.0	1.0
Mississippi	0.6	0.6	0.6	0.7	0.4	0.3	0.3
Missouri	0.2	0.5	0.5	0.6	0.3	0.4	0.4
Oklahoma	+	+	+	+	+	+	+
Texas	0.8	0.5	0.4	0.5	0.4	0.3	0.3
Ratoon	**2.5**	**1.0**	**2.1**	**2.5**	**2.3**	**3.0**	**2.5**
Arkansas	+	+	+	+	+	1.0	0.4
Florida	+	+	+	+	+	0.1	+
Louisiana	1.3	0.5	1.3	1.7	1.2	1.3	1.2
Texas	1.1	0.4	0.8	0.8	1.1	0.6	0.8
Total	**9.2**	**8.9**	**9.4**	**11.1**	**8.5**	**9.3**	**8.3**

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[4] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

[5] Oklahoma has also historically produced rice. 2007 was the most recent production year reported (77 hectares).

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Less than 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 5-11: CH_4 Emissions from Rice Cultivation (kt)

State	1990	2005	2009	2010	2011	2012	2013
Primary	**268**	**319**	**294**	**343**	**247**	**253**	**233**
Arkansas	115	157	141	171	111	123	103
California	34	45	48	48	50	48	48
Florida	1	1	1	1	2	1	2
Louisiana	52	50	45	51	40	38	40
Mississippi	24	25	23	29	15	12	12
Missouri	8	21	19	24	12	17	15
Oklahoma	+	+	+	+	+	+	+
Texas	34	19	16	18	17	13	14
Ratoon	**98**	**39**	**84**	**101**	**92**	**119**	**99**
Arkansas	+	1	+	+	+	41	17
Florida	2	+	2	2	2	2	2
Louisiana	52	22	51	68	46	50	50
Texas	45	17	31	32	44	26	31
Total	**366**	**358**	**378**	**444**	**339**	**372**	**332**

+ Less than 0.5 kt
Note: Totals may not sum due to independent rounding.

Methodology

IPCC (2006) recommends using harvested rice areas, and seasonally integrated emission factors (i.e., country specific emission factors that have been developed from standardized field measurements (representing the mix of different conditions that influence CH_4 emissions in the area) for each commonly occurring rice production system). To that end, the recommended GPG methodology and Tier 2 U.S.-specific seasonally integrated emission factors derived from U.S. based rice field measurements are used.

Regional emission factors were derived based on a literature review of recent research on CH_4 emissions from U.S. rice production. In California, some rice fields are flooded during the winter to prepare the fields for the next growing season, and to create waterfowl habitat (Young 2013). Winter flooded rice crops generate CH_4 year round due to the anaerobic conditions the winter flooding creates (Environmental Defense Fund 2011), and up to 50 percent of the CH_4 emissions occur in the winter (Fitzgerald et al. 2000). Thus for winter flooded rice crops in California, an annual CH_4 emission factor is used. For non-winter flooded California rice crops, a seasonal emission factor is applied as almost all of the CH_4 emissions occur during the growing season (Fitzgerald et al. 2000). California-specific winter flooded and non-winter flooded emission factors were applied to rice area harvested in California. Average U.S. seasonal emission factors were applied to Arkansas, Florida, Louisiana, Missouri, Mississippi, and Texas as there was not sufficient data to develop state-specific, or daily emission factors, or both. As described above, seasonal emissions are much higher for ratooned crops than for primary crops. Therefore, emissions from ratooned and primary areas are estimated separately using the appropriate representative emission factors. This approach is consistent with IPCC (2006).

To determine what CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments that involved atypical or non-representative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation, or floodwaters were drained mid-season), as well as experiments in which measurements were not made over an entire flooding season were excluded from the analysis. The remaining experimental results were then sorted by state, season (i.e., primary and ratoon), flooding practices, and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added).

Eleven California-specific primary crop experimental results were added for California rice emissions starting with the 1990-2012 Inventory. These California-specific studies were selected because they met the criteria of experiments on primary crops with added synthetic and organic fertilizer, without residue burning, and without winter flooding (Bossio et al. 1999; Fitzgerald et al. 2000). The seasonal emission rates estimated in these studies were averaged to derive a seasonal emission factor for California's primary, non-winter flooded rice crop. Similarly, separate California-specific studies meeting the same criteria, (i.e., primary crops with added synthetic and organic fertilizer, without residue burning) but with winter flooding (Bossio et al. 1999; Fitzgerald et al. 2000; McMillan et al. 2007) were averaged to derive an annual emission factor for California's primary, winter-flooded rice crop. Approximately 60 percent of California's rice crop is winter-flooded (Environmental Defense Fund 2011), therefore the California-specific, winter flooded emission factor was applied to 60 percent of the California rice area harvested and the California-specific, non-winter flooded emission factor was applied to the 40 percent of the California rice area harvested. The resultant seasonal emission factor for the California, non-winter flooded crop is 133 kg CH_4/hectare/season, and the annual emission factor for the California, winter-flooded crop is 266 kg CH_4/hectare/season.

For the remaining states, a non-California U.S. seasonal emission factor was derived by averaging seasonal emissions rates from primary crops with added synthetic and organic fertilizer (Byrd 2000; Kongchum 2005; Rogers et al. 2011; Sass et al. 1991a, 1991b, 2002a, 2002b; Yao 2001). The seasonal emissions rates from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993; Lindau et al. 1995) were averaged to derive a seasonal emission factor for the ratoon crop. The resultant seasonal emission factor for the primary crop is 237 kg CH_4/hectare/season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare/season.

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 5-12, and the ratooned crop area as a percent of primary crop area is shown in Table 5-13. Primary crop areas for 1990 through 2013 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987–1992* (USDA 1994), *Field Crops Final Estimates 1992–1997* (USDA 1998), *Field Crops Final Estimates 1997–2002* (USDA 2003), and *Crop Production Summary* (USDA 2005 through 2014). Source data for non-USDA sources of primary and ratoon harvest areas are shown in Table 5-14. California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2013 (Anderson 2008 through 2014; Beighley 2011 through 2012; Buehring 2009 through 2011; Guethle 1999 through 2010; Lee 2003 through 2007; Mutters 2001 through 2005; Street 1999 through 2003; Walker 2005, 2007 through 2008).

Table 5-12: Rice Area Harvested (Hectare)

State/Crop	1990	2005	2009	2010	2011	2012	2013
Arkansas							
Primary	485,633	661,675	594,901	722,380	467,017	520,032	433,023
Ratoon[a]	-	662	6	7	5	52,003	21,651
California	159,854	212,869	225,010	223,796	234,723	225,415	227,034
Florida							
Primary	4,978	4,565	5,664	5,330	8,212	6,244	6,739
Ratoon	2,489	-	2,266	2,275	2,311	2,748	2,159
Louisiana							
Primary	220,558	212,465	187,778	216,512	169,162	160,664	167,139
Ratoon	66,168	27,620	65,722	86,605	59,207	64,265	63,513
Mississippi	101,174	106,435	98,341	122,622	63,537	52,206	50,182
Missouri	32,376	86,605	80,939	101,578	51,801	71,631	63,132
Oklahoma	617	271	-	-	-	-	-
Texas							
Primary	142,857	81,344	68,798	76,083	72,845	54,229	58,276
Ratoon	57,143	21,963	39,903	41,085	56,091	33,080	39,628
Total Primary	**1,148,047**	**1,366,228**	**1,261,431**	**1,468,300**	**1,067,298**	**1,090,421**	**1,005,525**
Total Ratoon	**125,799**	**50,245**	**107,897**	**129,971**	**117,613**	**152,096**	**126,951**
Total	**1,273,847**	**1,416,473**	**1,369,328**	**1,598,271**	**1,184,911**	**1,242,517**	**1,132,476**

[a] Arkansas ratooning occurred only in 1998, 1999, and 2005 through 2013, with particularly high ratoon rates in 2012 and 2013.

"-" No reported value

Note: Totals may not sum due to independent rounding.

Table 5-13: Ratooned Area as Percent of Primary Growth Area

State	1990	2005	2009	2010	2011	2012	2013
Arkansas	+	0.1%	+	+	+	10%	5%
Florida	50%	+	40%	43%	28%	44%	32%
Louisiana	30%	13%	35%	40%	35%	40%	38%
Texas	40%	27%	58%	54%	77%	61%	68%

+ Indicates ratooning less than 0.05 percent of primary growth area.

Table 5-14: Non-USDA Data Sources for Rice Harvest Information

State/Crop	1990	2005	2009	2010	2011	2012	2013
Arkansas – Ratoon[a]	Slaton	Wilson	Wilson (2009 – 2011)			Hardke (2012 – 2013)	
Florida – Primary[b]	Schueneman	Gonzalez	Gonzalez (2009 – 2013)				
Florida – Ratoon[c]	Schueneman	Gonzalez	Gonzalez (2009 – 2013)				
Louisiana – Ratoon[d]	Linscombe	Linscombe	Linscombe (2009 -2013)				
Oklahoma – Primary[e]	Lee	Lee	Anderson (2009 – 2013)				
Texas – Ratoon[f]	Klosterboer	TAES	Texas Agricultural Experiment Station (TAES) (2009 – 2013)				

[a] Arkansas: *1990 – 2000* (Slaton 1999 through 2001); *2001 – 2011* (Wilson 2002 through 2007, 2009 through 2012). *2012 – 2013* (Hardke 2013, 2014).

[b] Florida - Primary: *1990 – 2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002 – 2004* (Kirstein 2003 through 2004, 2006); *2005 – 2013* (Gonzalez 2007 through 2014)

[c] Florida - Ratoon: *1990 – 2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002 – 2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004- 2005); *2005 – 2013* (Gonzalez 2007 through 2014)

[d] Louisiana: *1990 - 2013* (Linscombe 1999, 2001 through 2014).

[e] Oklahoma: *1990 – 2006* (Lee 2003 through 2007); *2007 – 2013* (Anderson 2008 through 2014).

[f] 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 – 2014).

Box 5-1: Comparison of the U.S. Inventory Seasonal Emission Factors and IPCC (1996) Default Emission Factors

Emissions from rice production were estimated using a Tier 2 methodology consistent with IPCC (2006). Representative emission factors using experimentally determined seasonal CH_4 emissions from U.S. rice fields for both primary and ratoon crops were derived from a literature review. Emissions are compared with the *1996 IPCC Guidelines* default U.S. seasonal emission factor, and not the more recent *2006 IPCC Guidelines* global daily emission factor. The rationale for this comparison is that the evaluated studies were specific to the U.S., were regional specific seasonal emission factors, and did not include daily emission factors or season length. As explained above, four different emission factors were calculated: (1) a seasonal, California-specific factor without winter flooding (133 kg CH_4/hectare/season), (2) an annual, California specific-factor with winter flooding (266 kg CH_4/hectare/year), (3) a seasonal, non-California primary crop factor (237 kg CH_4/hectare/season), and (4) a seasonal, non-California ratoon crop factor (780 kg CH_4/hectare/season). These emission factors represent averages across rice field measurements representing typical water management practices and synthetic and organic amendment application practices in the United States according to regional experts (Anderson 2013; Beighly 2012; Fife 2011; Gonzalez 2013; Linscombe 2013; Vayssières 2013; Wilson 2012). The IPCC (1996) default factor for U.S. (i.e., Texas) rice production for both primary and ratoon crops is 250 kg CH_4/hectare/season. This default value is based on a study by Sass and Fisher (1995) which reflects a growing season in Texas of approximately 275 days. Data results in the evaluated studies were provided as seasonal emission factors; therefore, neither daily emission factors nor growing season length was estimated. Some variability within season lengths in the evaluated studies is assumed. The Tier 2 emission factors used here represent rice cultivation practices specific to the United States. For comparison, the 2013 U.S. emissions from rice cultivation are 8.3 MMT CO_2 Eq. using the four U.S.-specific emission factors for both primary and ratoon crops and 7.2 MMT CO_2 Eq. using the IPCC (1996) emission factor.

Table 5-15: Non-California Seasonal Emission Factors (kg CH_4/hectare/season)

Primary		Ratoon	
Minimum	61	Minimum	481
Maximum	500	Maximum	1490
Mean	237	Mean	780

Table 5-16: California Emission Factors (kg CH_4/hectare/year or season)

Winter Flooded (Annual)[b]		Non-Winter Flooded (Seasonal)[c]	
Minimum	131	Minimum	62
Maximum	369	Maximum	221
Mean	266	Mean	133

Note: See methodology text for why the emission factor is annual for winter flooded and seasonal for non-winter flooded California rice production.

[b] Percentage of California rice crop winter flooded: 60 percent.

[c] Percentage of California rice crop not winter flooded: 40 percent.

Uncertainty and Time-Series Consistency

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This inherent variability is due to differences in cultivation practices, particularly fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 61 to 500 kg CH_4/hectare/season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare/season. The uncertainty distributions around the California winter flooding, California non-winter flooding, non-California primary, and ratoon emission factors were derived using the distributions of the relevant emission factors available in the literature and described above. Variability around the rice emission factor means was not normally distributed for any crop system, but rather skewed, with a tail trailing to the right of the mean. A lognormal statistical distribution was, therefore, applied in the uncertainty analysis.

Other sources of uncertainty include the primary rice-cropped area for each state, percent of rice-cropped area that is ratooned, the length of the growing season, and the extent to which flooding outside of the normal rice season is practiced. Expert judgment was used to estimate the uncertainty associated with primary rice-cropped area for each state at 1 to 5 percent, and a normal distribution was assumed. Uncertainties were applied to ratooned area by state, based on the level of reporting performed by the state. Within California, the uncertainty associated with the percentage of rice fields that are winter flooded was estimated at plus and minus 20 percent. No uncertainty estimates were calculated for the practice of flooding outside of the normal rice season outside of California because CH_4 flux measurements have not been undertaken over a sufficient geographic range or under a broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Approach 2) uncertainty analysis was performed using the information provided above. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-17. Rice cultivation CH_4 emissions in 2013 were estimated to be between 4.2 and 15.9 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 50 percent below to 91 percent above the actual 2013 emission estimate of 8.3 MMT CO_2 Eq.

Table 5-17: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	CH_4	8.3	4.2	15.9	-50%	91%

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for rice cultivation was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and cropping seasons to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations Chapter. As a result of the updated GWP value for CH_4, emissions estimates for each year from 1990 to 2012 increased by 19 percent relative to the emissions estimates in previous Inventory reports.

Additionally, the 2012 emission estimates were updated to reflect an increase in previously-reported ratooning in Arkansas. Rice was harvested early in 2012, after which a high percentage of "secondary growth" occurred. Estimated percent ratooning of secondary growth in 2012 increased from 5 to 10 percent (Hardke 2014), resulting in a 0.4 MMT CO_2 eq. (21 kt C) increase in emissions.

Planned Improvements

A planned improvement for the 1990 through 2014 Inventory will be the expansion of the California-specific rice emission factors to include an emission factor for the period prior to the passage of the Air Resources Board (ARB) Mandate phasing out rice residue burning. This non-flooded residue burned emission factor will take into account the phase down of rice straw burning that occurred in California from 1990 to 2002. During this time period, the percentage of acres burned annually decreased from 75 percent in 1992 to 13 percent in 2002 (California Air Resources Board 2003). California studies that include rice burning on non-flooded lands will be used to develop the pre-2002 rice burning emission factor, and further research will be conducted to determine the percentage of winter flooded area to which the current California winter flooded emission factor will be applied. This new time series dependent emission factor will be applied to non-flooded burned area during the 1990 through 2002 time period to capture the significant change in the percentage of rice area burned due to the California ARB Mandate. Following 2002, the current methodology and emission factors will be applied.

Another possible future improvement is to create additional state- or region-specific emission factors for rice cultivation. This prospective improvement would likely not take place for another two to three years, because the analyses needed for it are currently taking place.

5.4 Agricultural Soil Management (IPCC Source Category 3D)

Nitrous oxide (N_2O) is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral N (Firestone and Davidson 1989).[6] Mineral N is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere.[7] A number of agricultural activities directly or indirectly increase mineral nitrogen (N) availability in soils, and therefore influence N_2O emissions occurring through nitrification and denitrification (see Figure 5-2) (Mosier et al. 1998). Direct N increases occur through a variety of management practices, including fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and drainage of organic soils (i.e., soils with a high organic matter content, otherwise known as Histosols[8]) in croplands and grasslands (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization by impacting moisture and temperature regimes in soils. Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water.[9]

Direct and indirect emissions from agricultural lands (i.e., cropland and grassland as defined in Chapter 6.1 Representation of the U.S. Land Base) are included in this section. As recommended by the IPCC (2006), N mineralization from decomposition of soil organic matter and asymbiotic N fixation is also included in this section for complete accounting of management impacts on greenhouse gas emission from managed land (see Methodology section for more information).

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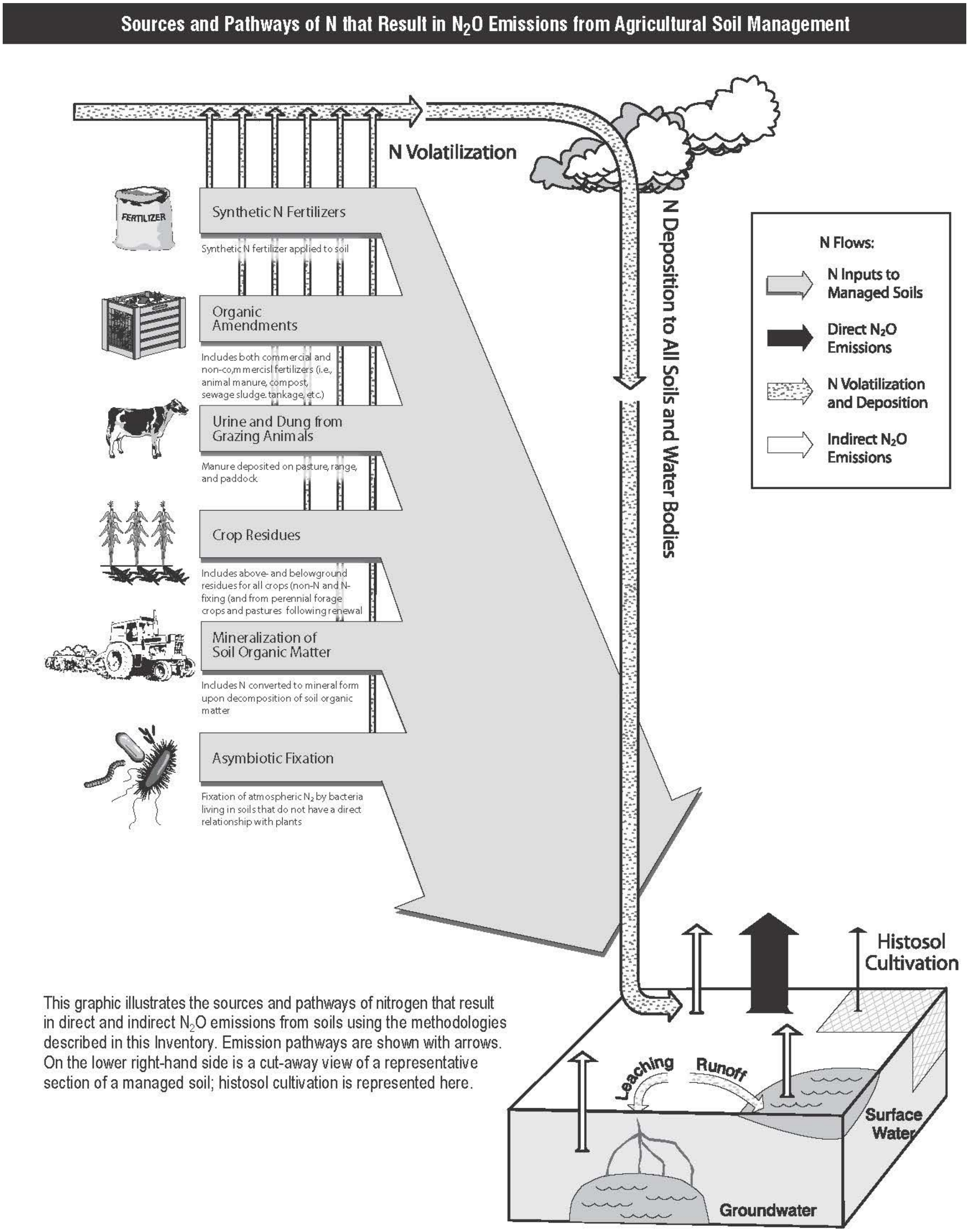
[6] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well-understood mechanism (Nevison 2000).

[7] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[8] Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

[9] These processes entail volatilization of applied or mineralized N as NH_3 and NO_x, transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x.

Figure 5-2: Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils using the methodologies described in this Inventory. Emission pathways are shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2013 were 263.7 MMT CO_2 Eq. (885 kt) (see Table 5-18 and Table 5-19) Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2013, although overall emissions were 17.7 percent higher in 2013 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2013, on average cropland accounted for approximately 62 percent of total direct emissions, while grassland accounted for approximately 38 percent. The percentages for indirect emissions on average are approximately 81 percent for croplands, 19 percent for grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-20 and Table 5-21.

Table 5-18: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
Direct	**190.8**	**208.6**	**225.3**	**225.4**	**226.3**	**226.1**	**224.7**
Cropland	117.1	130.6	136.0	136.2	137.2	137.6	135.7
Grassland	73.7	78.1	89.4	89.2	89.1	88.5	89.0
Indirect	**33.2**	**35.0**	**38.8**	**38.8**	**39.5**	**39.8**	**39.0**
Cropland	26.4	28.1	31.8	31.9	32.6	32.9	32.1
Grassland	6.8	6.9	6.9	6.9	6.9	6.9	6.9
Total	**224.0**	**243.6**	**264.1**	**264.3**	**265.8**	**266.0**	**263.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Table 5-19: N_2O Emissions from Agricultural Soils (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
Direct	**640**	**700**	**756**	**757**	**759**	**759**	**754**
Cropland	393	438	456	457	460	462	455
Grassland	247	262	300	299	299	297	299
Indirect	**111**	**117**	**130**	**130**	**133**	**134**	**131**
Cropland	88	94	107	107	109	110	108
Grassland	23	23	23	23	23	23	23
Total	**752**	**817**	**886**	**887**	**892**	**892**	**885**

Table 5-20: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
Cropland	**117.1**	**130.6**	**136.0**	**136.2**	**137.2**	**137.6**	**135.7**
Mineral Soils	**114.4**	**128.0**	**133.5**	**133.7**	**134.7**	**135.1**	**133.2**
Synthetic Fertilizer	49.4	54.3	57.8	59.2	60.2	60.7	58.8
Organic Amendment[a]	11.2	12.5	13.1	13.0	13.2	13.3	13.2
Residue N[b]	6.2	6.3	6.3	6.2	6.0	5.9	6.2
Mineralization and Asymbiotic Fixation	47.7	54.9	56.3	55.3	55.3	55.2	54.9
Organic Soils	**2.7**	**2.6**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Grassland	**73.7**	**78.1**	**89.4**	**89.2**	**89.1**	**88.5**	**89.0**
Mineral Soils	**71.4**	**75.8**	**87.2**	**87.1**	**86.9**	**86.4**	**86.9**
Synthetic Fertilizer	1.9	1.8	1.9	1.9	2.0	2.1	2.2
PRP Manure	16.5	17.5	18.2	18.0	17.6	17.2	17.2
Managed Manure[c]	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Sewage Sludge	0.2	0.5	0.5	0.5	0.5	0.6	0.6
Residue N[d]	1.8	2.1	2.3	2.3	2.3	2.3	2.3
Mineralization and Asymbiotic Fixation	50.7	53.6	64.0	64.0	64.1	63.9	64.3
Organic Soils	**2.3**	**2.2**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**
Total	**190.8**	**208.6**	**225.3**	**225.4**	**226.3**	**226.1**	**224.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[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 N inputs include N in unharvested legumes as well as crop residue N.

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[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.

[d] Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N

Table 5-21: Indirect N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990		2005		2009	2010	2011	2012	2013
Cropland	**26.4**		**28.1**		**31.8**	**31.9**	**32.6**	**32.9**	**32.1**
Volatilization & Atm. Deposition	13.1		14.5		14.4	14.4	14.8	14.9	14.7
Surface Leaching & Run-Off	13.2		13.5		17.5	17.4	17.8	18.0	17.4
Grassland	**6.8**		**6.9**		**6.9**	**6.9**	**6.9**	**6.9**	**6.9**
Volatilization & Atm. Deposition	4.2		4.5		4.5	4.5	4.5	4.5	4.4
Surface Leaching & Run-Off	2.7		2.4		2.5	2.5	2.5	2.5	2.5
Total	**33.2**		**35.0**		**38.8**	**38.8**	**39.5**	**39.8**	**39.0**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Figure 5-3 and Figure 5-4 show regional patterns for direct N_2O emissions for croplands and grasslands, and Figure 5-5 and Figure 5-6 show N losses from volatilization, leaching, and runoff that lead to indirect N_2O emissions. Annual emissions and N losses in 2013 are shown for the Tier 3 Approach only.

Direct N_2O emissions from croplands tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern and western Minnesota, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops (Figure 5-3). Kansas has high direct emissions associated with N management in wheat production systems. Hay production in Missouri and irrigated cropping systems in California also contribute relatively large amounts of direct N_2O emissions, along with a combination of irrigated cropping in the west Texas and hay production in east Texas. Direct emissions are low in many parts of the eastern United States because only a small portion of land is cultivated and in many western states where rainfall and access to irrigation water are limited.

Direct emissions from grasslands are highest in the central and western United States (Figure 5-4) where a high proportion of the land is used for cattle grazing. In contrast, most areas in the Great Lake states, the Northeast, and Southeast have moderate to low emissions due to less land dedicated to livestock grazing. However, emissions from the Northeast and Great Lake states tend to be higher on a per unit area basis compared to other areas in the country. This effect is likely due to a larger impact of freeze-thaw cycles in these regions, and possibly greater water-filled pore space in the soil, which is key driver of N_2O emissions (Kessavalou et al. 1998, Bateman and Baggs 2005).

Indirect emissions from croplands and grasslands (Figure 5-5 and Figure 5-6) show similar emission patterns to those of direct emissions because the same driving variables (N inputs, weather patterns, soil characteristics) are controlling both types of emissions. There are some exceptions to the similarity in patterns, however, because the processes that contribute to indirect emissions (NO_3^- leaching, N volatilization) do not respond in exactly the same manner to the driving variables as the processes that contribute to direct emissions (nitrification and denitrification).

Figure 5-3: Crops, Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2013 (MMT CO_2 Eq./year)

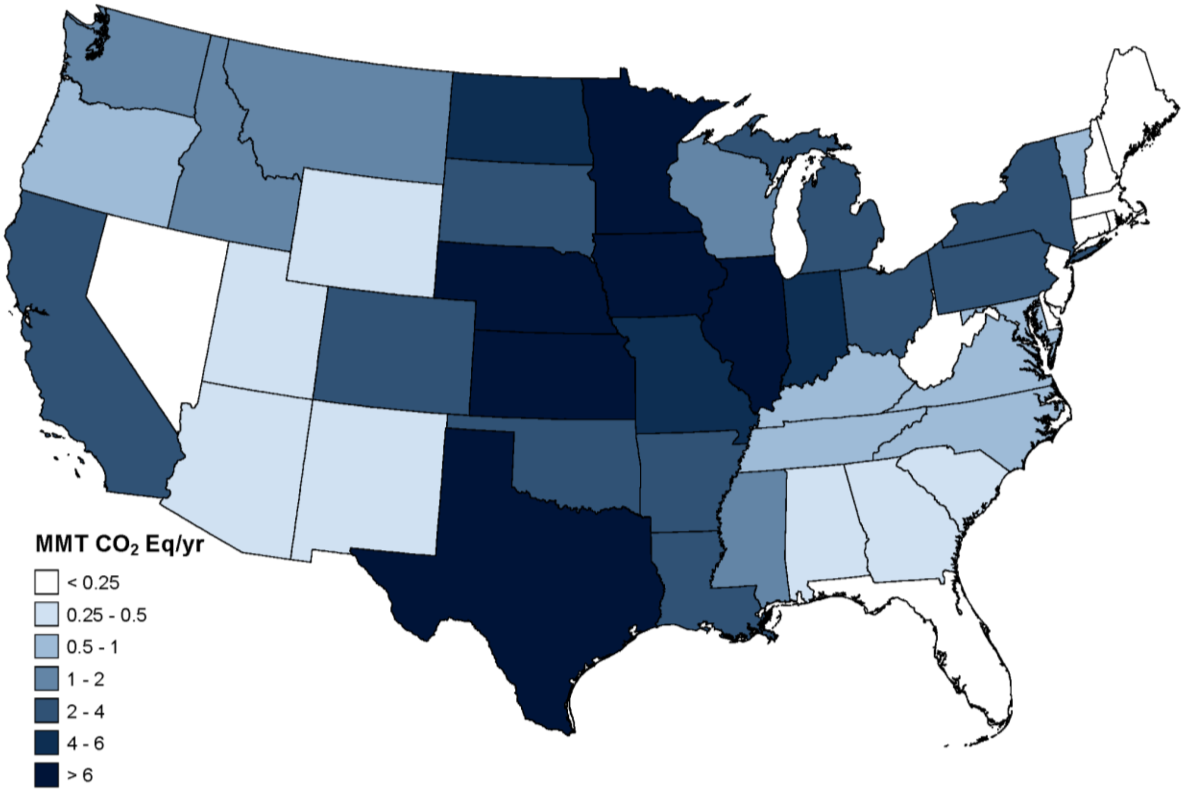


Figure 5-4: Grasslands, Annual Direct N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2013 (MMT CO_2 Eq./year)

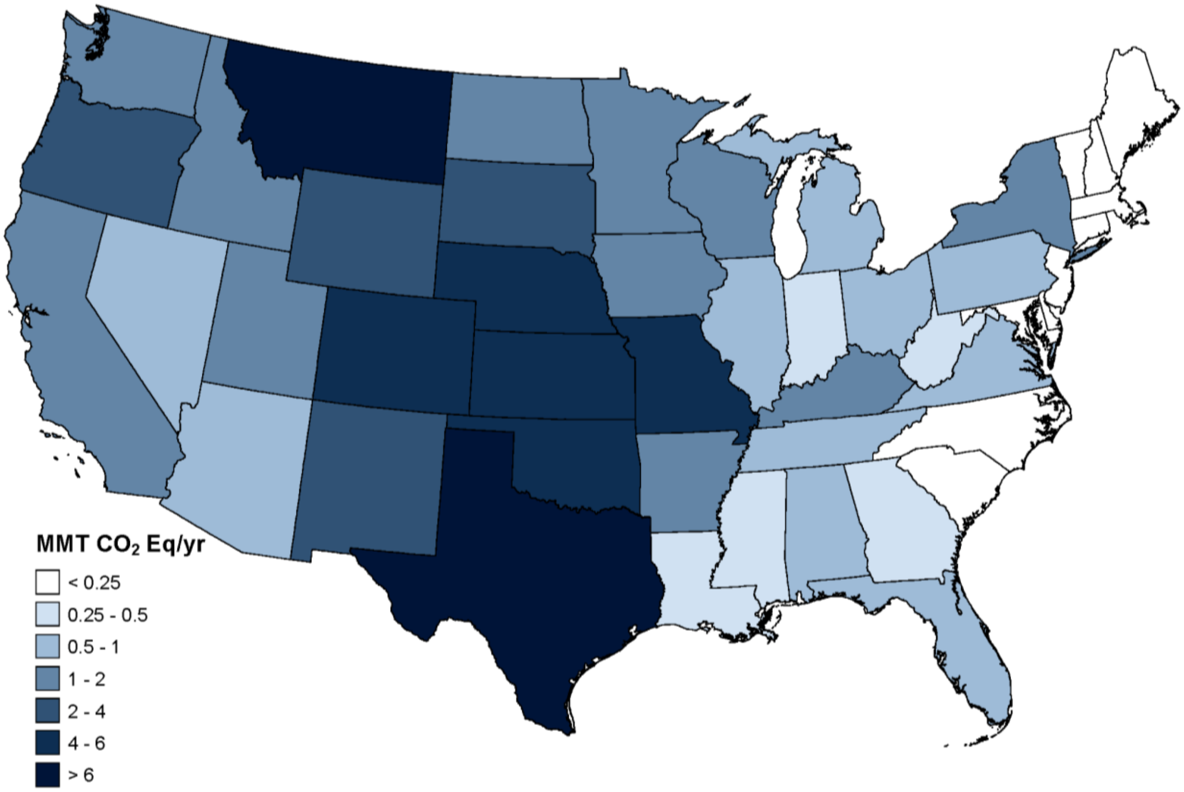


Figure 5-5: Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2013 (kt N/year)

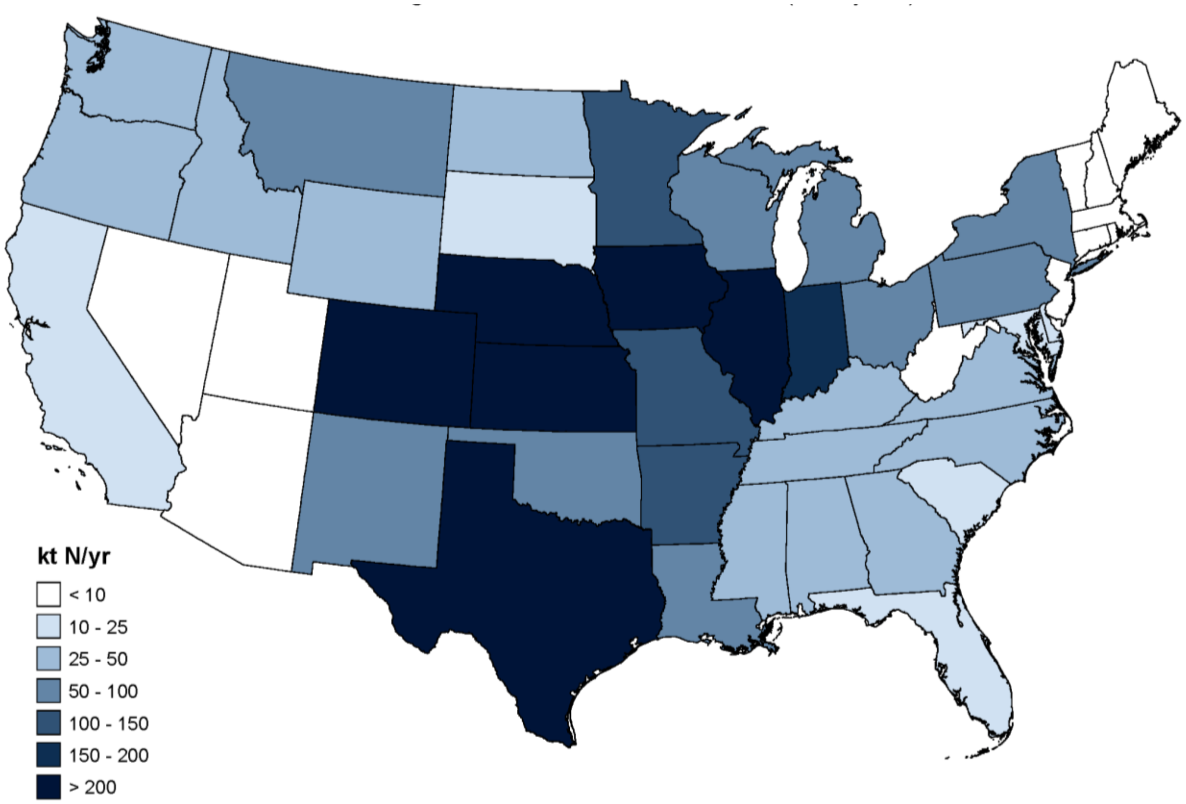
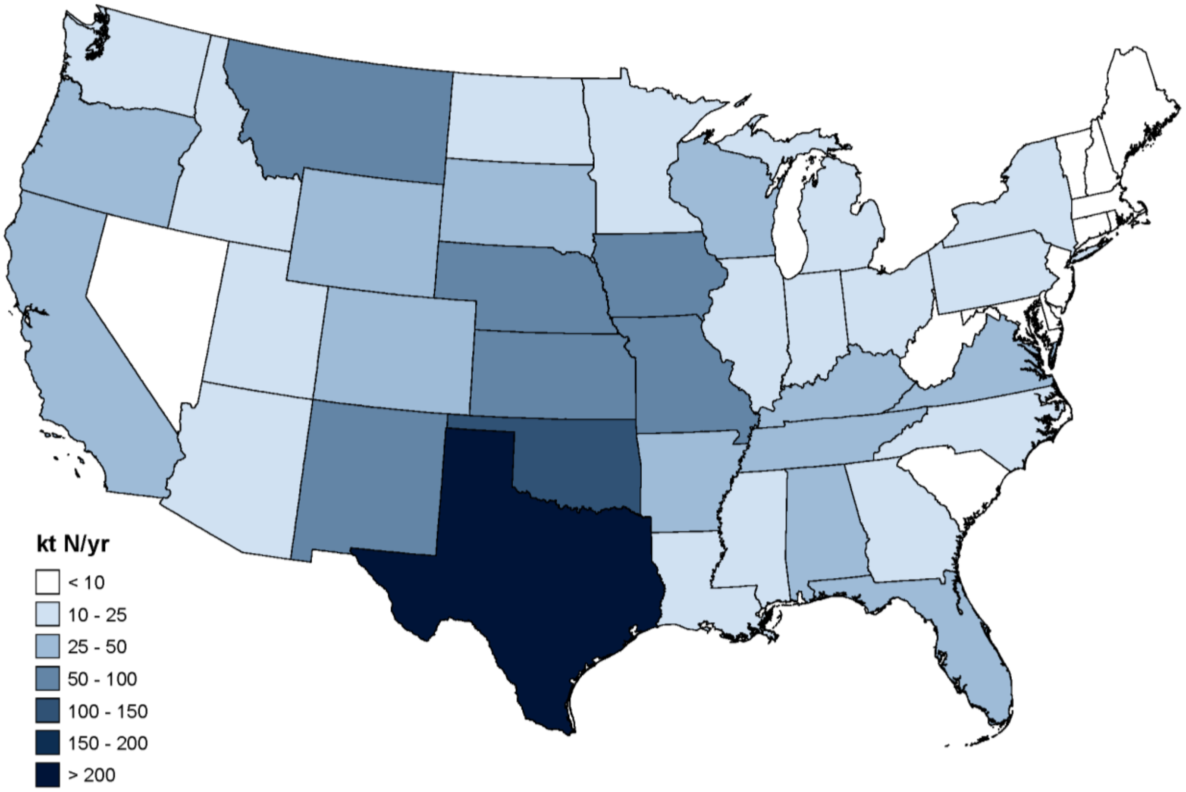


Figure 5-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the Tier 3 DAYCENT Model, 1990-2013 (kt N/year)



Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the *Agricultural Soil Management* source category into five components, including (1) direct emissions from N additions to cropland and grassland mineral soils from synthetic fertilizers, sewage sludge applications, crop residues, organic amendments, and biological N fixation associated with planting of legumes on cropland and grassland soils; (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 N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

The United States has adopted recommendations from IPCC (2006) on methods for agricultural soil management. These recommendations include (1) estimating the contribution of N in crop residues to indirect soil N_2O emissions; (2) adopting the revised emission factor for direct N_2O emissions for Tier 1 methods used in the Inventory (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils from harvest yield data; and (5) estimating emissions associated with land use and management change (which can significantly change the N mineralization rates from soil organic matter).[10] The Inventory also reports on total emissions from all managed land, which is a proxy for anthropogenic impacts on greenhouse gas emissions (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation and mineralization of

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[10] N inputs from asymbiotic N fixation are not directly addressed in *2006 IPCC Guidelines*, but are a component of the total emissions from managed lands and are included in the Tier 3 approach developed for this source.

soil organic matter and litter. One recommendation from IPCC (2006) that has not been completely adopted is the accounting of emissions from pasture renewal, which involves occasional plowing to improve forage production in pastures. The exception is pastures that are replanted occasionally in rotation with annual crops, this practice is represented in the 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 (IPCC 2006, Del Grosso et al. 2010). A Tier 3 process-based model (DAYCENT) was used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat; as well as the direct emissions from non-federal grasslands with the exception of sewage sludge amendments (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 5-2 for further elaboration). Moreover, the Tier 3 approach allows for the Inventory to address direct N_2O emissions and soil C stock changes from mineral cropland soils in a single analysis. Carbon and N 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 C and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are taken into account between C and N cycling in soils.

The Tier 3 approach is based on the cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2009). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 points in agricultural land for the conterminous United States that are included in the Tier 3 methods.[11] Each point is associated with an "expansion factor" that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979-1982, 1984-1987, 1989-1992, and 1994-1997). In 1998, the NRI program began collecting annual data, the annual data are currently available through 2010 (USDA-NRCS 2013) although this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory.

Box 5-2: 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 N inputs (e.g., synthetic fertilizer, manure, N 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 N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs and the environmental conditions at specific locations. Consequently, the Tier 3 approach produces more accurate estimates; it accounts more comprehensively for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific N amendment rates), additional data inputs (e.g., daily weather, soil types, etc.), 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 the adequacy of the method for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N 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.

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[11] NRI points were classified as "agricultural" if under grassland or cropland management between 1990 and 2007. There are another 148,731 NRI survey points that are cropland and are not included in the Tier 3 analysis. The soil N_2O emissions associated with these points are estimated with the IPCC Tier 1 method.

This is a simplifying assumption that is likely to create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes the legacy effect of N added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

DAYCENT was not used to estimate N_2O emissions for all land areas. DAYCENT was used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, but was not applied to estimate N_2O emissions from other crops or rotations with other crops[12], such as sugarcane, some vegetables, tobacco, 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, were not simulated with DAYCENT. DAYCENT was also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), or to estimate emissions from 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 were not simulated with DAYCENT due to limited activity on land use histories. Consequently, the Tier 1 IPCC (2006) methodology was used to estimate (1) direct emissions from crops on mineral soils that are not simulated by DAYCENT; (2) direct emissions from Pasture/Range/Paddock (PRP) on federal grasslands, which were not estimated with the Tier 3 DAYCENT model; and (3) direct emissions from drainage of organic soils in croplands and grasslands.

Tier 3 Approach for Mineral Cropland Soils

The DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) was used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops based on the cropping histories in the 2009 NRI (USDA-NRCS 2009). The crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. Crops simulated by DAYCENT are grown on approximately 93 percent of total cropland area in the United States. For agricultural systems in the central region of the United States, crop production for key crops (i.e., corn, soybeans, sorghum, cotton and wheat) is simulated in DAYCENT with a NASA-CASA production algorithm (Potter et al.1993; Potter et al. 2007) using the MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250m.[13] A prediction algorithm was developed to estimate EVI (Gurung et al. 2009) for gap-filling during years over the Inventory time series when EVI data were not available (e.g., data from the MODIS sensor were only available after 2000 following the launch of the Aqua and Terra Satellites; see Annex 3.12 for more information). DAYCENT also simulated soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions.

DAYCENT was used to estimate direct N_2O emissions due to mineral N available from the following sources: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues and subsequent mineralization of N during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); and (4) mineralization of soil organic matter, in addition to asymbiotic fixation. Note that commercial organic fertilizers (TVA 1991 through 1994; AAPFCO 1995 through 2011) are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model.

Synthetic fertilizer data were based on fertilizer use and rates by crop type for different regions of the United States that were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of livestock manure application to cropland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted

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[12] 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.

[13] See <https://lpdaac.usgs.gov/products/modis_products_table>.

using county-level estimates of manure available for application in other years. The adjustments were based on county-scale ratios of manure available for application to soils in other years relative to 1997 (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 was assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area. Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. N losses include direct N_2O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. For unmanaged systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil. More information on livestock manure production is available in the Manure Management Section 5.2 and Annex 3.11.

The IPCC approach considers crop residue N and N mineralized from soil organic matter as activity data. However, they are not treated as activity data in DAYCENT simulations because residue production, symbiotic N fixation (e.g., legumes), mineralization of N from soil organic matter, and asymbiotic N fixation are internally generated by the model as part of the simulation. In other words, DAYCENT accounts for the influence of symbiotic N fixation, mineralization of N from soil organic matter and crop residue retained in the field, and asymbiotic N fixation on N_2O emissions, but these are not model inputs. The DAYCENT simulations also accounted for the approximately 3 percent of all crop residues that were assumed to be burned based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996), and therefore N_2O emissions were reduced by 3 percent from crop residues to account for the burning.

Additional sources of data were used to supplement the mineral N (USDA ERS 1997, 2011), livestock manure (Edmonds et al. 2003), and land-use information (USDA-NRCS 2009). The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity with adjustments for long-term adoption of no-till agriculture (Towery 2001). Tillage data has an influence on soil organic matter decomposition and subsequent soil N_2O emissions. The time series of tillage data began in 1989 and ended in 2004, so further changes in tillage practices since 2004 are not currently captured in the Inventory. Daily weather data were used as an input in the model simulations, based on gridded weather data at a 32 km scale from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). Soil attributes were obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011).

Each 2009 NRI point was run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulations for the analysis. Soil N_2O emission estimates from DAYCENT were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but emissions from 2008 to 2013 were assumed to be similar to 2007. Annual data are currently available through 2010 (USDA-NRCS 2013). However, this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N 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 mineral N added to the soil for each of these sources was determined and then divided by the total amount of mineral N that was made available in the soil according to the DAYCENT model. The percentages were then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to key practices. This approach is only an approximation because it assumes that all N 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 N, 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 N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology was used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DAYCENT. For the Tier 1 Approach, estimates of direct N_2O emissions from N applications were based on mineral soil N that was 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) the retention of above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure, commercial organic amendments were not included in the DAYCENT simulations because county-level data were not available.[14] Consequently, commercial organic fertilizer, as well as additional manure that was not added to crops in the DAYCENT simulations, were included in the Tier 1 analysis. The following sources were used to derive activity data:

- A process-of-elimination approach was used to estimate synthetic N fertilizer additions for crop areas not simulated by DAYCENT. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. For 2002 through 2013, state-level fertilizer for on-farm use is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2007, AAPFCO 2008 through 2014).[15] After subtracting the portion of fertilizer applied to crops and grasslands simulated by DAYCENT (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied to crops that were not simulated by DAYCENT.
- Similarly, a process-of-elimination approach was used to estimate manure N additions for crops that were not simulated by DAYCENT. The amount of manure N applied in the Tier 3 approach to crops and grasslands was subtracted from total manure N available for land application (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), and this difference was assumed to be applied to crops that are not simulated by DAYCENT.
- Commercial organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content (TVA 1991 through 1994; AAPFCO 1995 through 2011). Commercial fertilizers do include some manure and sewage sludge, but the amounts are removed from the commercial fertilizer data to avoid double counting with the manure N dataset described above and the sewage sludge amendment data discussed later in this section.
- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA-NASS 2014), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

The total increase in soil mineral N from applied fertilizers and crop residues was multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 Approach.

Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 methods were used to estimate direct N_2O emissions due to drainage of organic soils in croplands or grasslands at a state scale. State-scale estimates of the total area of drained organic soils were obtained from the 2009 NRI (USDA-NRCS 2009) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). Temperature data from Daly et al. (1994, 1998) were used to subdivide areas into temperate and tropical climates using the climate classification from IPCC (2006). Annual data were available between 1990 and 2007. Emissions are assumed to be similar to 2007 from 2008 to 2013 because no additional activity data are currently available from the NRI for the latter years. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total tropical area was multiplied by the IPCC default emission factor for tropical regions (IPCC 2006).

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[14] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and sewage sludge is removed from the dataset in order to avoid double counting with other datasets that are used for manure N and sewage sludge.

[15] Values were not available for 2013 so a "least squares line" statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value.

Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 method described in IPCC (2006) were combined to estimate emissions from non-federal grasslands and PRP manure N additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass forage primarily 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 addition management, such as irrigation or interseeding legumes. DAYCENT was used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2009) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as Daily Spread), and synthetic fertilizer application. Other N inputs were simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the Tier 3 Approach for Mineral Cropland Soils section. Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in the Manure Management section (5.2 Manure Management (IPCC Source Category 3B)) and Annex 3.11. Biological N fixation is simulated within DAYCENT, and therefore was not an input to the model.

Manure N deposition from grazing animals in PRP systems (i.e., PRP manure) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal grasslands for each NRI point were based on amount of N excreted by livestock in PRP systems. The total amount of N excreted in each county was divided by the grassland area to estimate the N input rate associated with PRP manure. The resulting input rates were used in the DAYCENT simulations. DAYCENT simulations of non-federal grasslands accounted for approximately 68 percent of total PRP manure N in aggregate across the country. The remainder of the PRP manure N in each state was assumed to be excreted on federal grasslands, and the N_2O emissions were estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. Sewage sludge was assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application was estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments to agricultural lands were only available at the national scale, and it was not possible to associate application with specific soil conditions and weather at the county scale. Therefore, DAYCENT could not be used to simulate the influence of sewage sludge amendments on N_2O emissions from grassland soils, and consequently, emissions from sewage sludge were estimated using the IPCC (2006) Tier 1 method.

Grassland area data were consistent with the Land Representation reported in Section 0 for the conterminous United States. Data were obtained from the U.S. Department of Agriculture NRI (Nusser and Goebel 1998) and the U.S. Geological Survey (USGS) National Land Cover Dataset (Vogelman et al. 2001), which were reconciled with the Forest Inventory and Analysis Data. The area data for pastures and rangeland were aggregated to the county level to estimate non-federal and federal grassland areas.

N_2O emissions for the PRP manure N deposited on federal grasslands and applied sewage sludge N were estimated using the Tier 1 method by multiplying the N input by the appropriate emission factor. Emissions from manure N were estimated at the state level and aggregated to the entire country, but emissions from sewage sludge N were calculated exclusively at the national scale.

As previously mentioned, each NRI point was simulated 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. Soil N_2O emission estimates from DAYCENT were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). Soil N_2O emissions and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but emissions from 2008 to 2013 were assumed to be similar to 2007. The annual data are currently available through 2010 (USDA-NRCS 2013). However, this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for cropland mineral soils, from drainage and cultivation of organic cropland soils, and from grassland soils were summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-18 and Table 5-19).

Indirect N_2O Emissions

This section describes the methods used for estimating indirect soil N_2O emissions from croplands and grasslands. Indirect N_2O emissions occur when mineral N 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 N as NO_x and NH_3 following application of synthetic fertilizer, organic amendments (e.g., manure, sewage sludge), and deposition of PRP manure. N made available from mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and input of N from asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion of the deposited N is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO_3) that was made available through anthropogenic activity on managed lands, mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and inputs of N into the soil from asymbiotic fixation. The NO_3^- 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 N for reporting purposes, which here includes croplands and grasslands.

Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N

The Tier 3 DAYCENT model and IPCC (2006) Tier 1 methods were combined to estimate the amount of N that was volatilized and eventually emitted as N_2O. DAYCENT was used to estimate N volatilization for land areas whose direct emissions were simulated with DAYCENT (i.e., most commodity and some specialty crops and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section. N volatilization for all other areas was estimated using the Tier 1 method and default IPCC fractions for N subject to volatilization (i.e., N inputs on croplands not simulated by DAYCENT, PRP manure N excreted on federal grasslands, sewage sludge application on grasslands). For the volatilization data generated from both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N_2O emissions occurring due to re-deposition of the volatilized N (Table 5-21).

Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 method were combined to estimate the amount of N that was subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DAYCENT was used to simulate the amount of N transported from lands in the Tier 3 Approach. N transport from all other areas was estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of N subject to leaching and runoff. This N transport estimate includes N applications on croplands that were not simulated by DAYCENT, sewage sludge amendments on grasslands, and PRP manure N excreted on federal grasslands. For both the DAYCENT Tier 3 and IPCC (2006) Tier 1 methods, nitrate leaching was 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 nitrate 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 plus irrigation does not exceed 80 percent of PET. For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N_2O emissions that occur in groundwater and waterways (Table 5-21).

Uncertainty and Time-Series Consistency

Uncertainty was 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 (N volatilized and leached or runoff) simulated by DAYCENT; (3) direct emissions approximated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) approximated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which account for the majority of N_2O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT were estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). Uncertainties in direct emissions calculated with the IPCC (2006) Approach 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Approach 1 method, and indirect N_2O emissions were estimated with a simple error propagation approach (IPCC 2006). Uncertainties from the Approach 1 and Approach 3 (i.e., DAYCENT) estimates were combined using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. The combined uncertainty for direct soil N_2O emissions ranged from 16 percent below to 26 percent above the 2013 emissions estimate of 224.7 MMT CO_2 Eq., and the combined uncertainty for indirect soil N_2O emissions ranged from 46 percent below to 160 percent above the 2013 estimate of 39.0 MMT CO_2 Eq.

Table 5-22: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2013 (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	224.7	189.2	282.4	-16%	26%
Indirect Soil N_2O Emissions	N_2O	39.0	21.2	101.6	-46%	160%

Note: Due to lack of data, uncertainties in managed manure N production, PRP manure N production, other organic fertilizer amendments, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

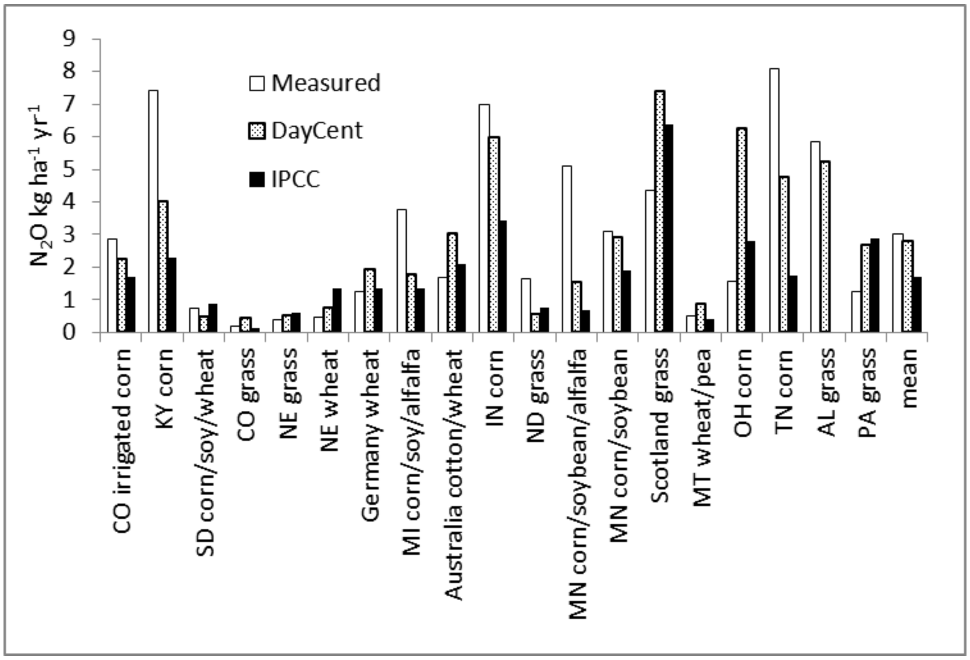
Additional uncertainty is associated with the lack of an estimation of N_2O emissions for croplands and grasslands in Hawaii and Alaska, with the exception of drainage for organic soils in Hawaii. Agriculture is not extensive in either state, so the emissions are likely to be small compared to the conterminous United States.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section above.

QA/QC and Verification

DAYCENT results for N_2O emissions and NO_3^- leaching were 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 to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. N_2O measurement data were available for 21 sites in the United States, 4 in Europe, and one in Australia, representing over 60 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N_2O emissions were closer to measured values at most sites compared to the IPCC Tier 1 estimate (Figure 5-7). In general, IPCC Tier 1 methodology tends to over-estimate emissions when observed values are low and under-estimate emissions when observed values are high, while DAYCENT estimates are less biased. DAYCENT accounts for key site-level factors (weather, soil characteristics, and management) that are not addressed in the IPCC Tier 1 Method, and thus the model is better able to represent the variability in N_2O emissions. Nitrate leaching data were available for four sites in the United States, representing 12 different combinations of fertilizer amendments/tillage practices. DAYCENT does have a tendency to under-estimate very high N_2O emission rates; estimates are increased to correct for this bias based on a statistical model derived from the comparison of model estimates to measurements (See Annex 3.12 for more information). Regardless, the comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions and NO_3^- leaching, and is an improvement over the IPCC Tier 1 method.

Figure 5-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach.



Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of croplands and grasslands and unit conversion factors were checked, as were the program scripts that were used to run the Monte Carlo uncertainty analysis. Links between spreadsheets were checked, updated, and corrected when necessary. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach were checked and an error was found relating to residue N inputs. Some crops that were simulated by DAYCENT were also included in the Tier 1 method. To correct this double-counting of N inputs, residue inputs from crops simulated by DAYCENT were removed from the Tier 1 calculations.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4, HFCs, and PFCs. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations Chapter.

Methodological recalculations in the current Inventory were associated with the following improvements: 1) Driving the DAYCENT simulations with updated input data for the excretion of C and N onto PRP and N additions from managed manure based on national livestock population (note that revised total PRP N additions decreased from 4.4 to 4.1 MMT N on average and revised managed manure additions decreased from 2.9 to 2.7 MMT N on average); 2) properly accounting for N inputs from residues for crops not simulated by DAYCENT; (3) modifying the number of experimental study sites used to quantify model uncertainty for direct N_2O emissions and bias correction; and (4) reporting indirect N_2O emissions from forest land and settlements in their respective sections, instead of the agricultural soil management section. These changes resulted in a decrease in emissions of approximately 18 percent on average relative to the previous Inventory and a decrease in the upper bound of the 95 percent confidence interval for direct N_2O emissions from 29 to 26 percent. The differences are mainly due to changing the number of study sites used to quantify model uncertainty and correct bias. Specifically, two sites were removed because they had a relatively small number of daily N_2O measurements, which tended to be anomalously high, so the validity of extrapolating annual emission estimates was questionable for those data.

Planned Improvements

Several planned improvements are underway:

(1) Improvements to update the time series of land use and management data from the 2010 USDA NRI so that it is extended from 2008 through 2010. Fertilization and tillage activity data will also be updated as part of this improvement. The remote-sensing based data on the Enhanced Vegetation Index will be extended through 2010 in order to use the EVI data to drive crop production in DAYCENT. The update will extend the time series of activity data for the Tier 2 and 3 analyses through 2010, and incorporate the latest changes in agricultural production for the United States;

(2) Improvements for the DAYCENT biogeochemical model. Model structure will be improved with a better representation of plant phenology, particularly senescence events following grain filling in crops, such as wheat. In addition, crop parameters associated with temperature effects on plant production will be further improved in DAYCENT with additional model calibration. Experimental study sites will continue to be added for quantifying model structural uncertainty. Studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013) will be given priority because they provide more robust estimates of annual emissions compared to studies that sample trace gas emissions weekly or less frequently;

(3) Improvements to account for the use of fertilizers formulated with nitrification inhibitors in addition to slow-release fertilizers (e.g., polymer-coated fertilizers). Field data suggests that nitrification inhibitors and slow-release fertilizers reduce N_2O emissions significantly. The DAYCENT model can represent nitrification inhibitors and slow-release fertilizers, but accounting for these in national simulations is contingent on testing the model with a sufficient number of field studies and collection of activity data about the use of these fertilizers;

(4) Improvements 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 (Section 5.5). The methodology for *Field Burning of Agricultural Residues* was significantly updated recently, but the new estimates of crop residues burned have not been incorporated into the *Agricultural Soil Management* source. Moreover, the data have only been used to reduce the N_2O after DAYCENT simulations in the current Inventory, but the planned improvement is to drive the simulations with burning events based on the new spatial data that is used in Section 5.5; and

(5) Alaska and Hawaii are not included in the current Inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in croplands and grasslands for Hawaii. A planned improvement over the next two years is to add these states into the Inventory analysis.

5.5 Field Burning of Agricultural Residues (IPCC Source Category 3F)

Crop production results in both harvested product(s) and large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be: left on or plowed into the field; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; landfilled; or, as discussed in this section, burned in the field. Field burning of crop residues is not considered a net source of CO_2, because the C released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, 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 commonly occurs in the southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops whose residues may be burned are corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). Rice, sugarcane, and wheat residues account for approximately 70 percent of all crop residue burning and emissions (McCarty 2011). In 2013, CH_4 and N_2O emissions from Field Burning of Agricultural Residues were 0.3 MMT CO_2 Eq. (12 kt) and 0.1 MMT. CO_2 Eq. (0.3 kt), respectively. Annual emissions from this source from 1990 to 2013 have remained relatively constant, averaging approximately 0.3 MMT CO_2 Eq. (12 kt) of CH_4 and 0.1 MMT CO_2 Eq. (0.3 kt) of N_2O (see Table 5-23 and Table 5-24).

Table 5-23: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2009	2010	2011	2012	2013
CH_4	**0.3**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	+	+	+	+
Sugarcane	0.1	+	+	+	+	+	+
Wheat	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
Total	**0.4**	**0.3**	**0.4**	**0.3**	**0.4**	**0.4**	**0.4**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Less than 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-24: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2009	2010	2011	2012	2013
CH_4	**13**	**9**	**12**	**11**	**12**	**12**	**12**
Corn	1	1	2	2	2	2	2
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	2	2	2	2	2	2	2
Soybeans	1	1	1	1	1	1	1
Sugarcane	3	1	2	2	2	2	2
Wheat	6	4	5	5	5	5	5
N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
CO	**268**	**184**	**247**	**241**	**255**	**253**	**262**
NO_x	**8**	**6**	**8**	**8**	**8**	**8**	**8**

+ Less than 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methodology

A U.S.-specific Tier 2 method was used to estimate greenhouse gas emissions from Field Burning of Agricultural Residues. The Tier 2 methodology used is consistent with the *2006 IPCC Guidelines* (for more details, see Box 5-3). In order to estimate the amounts of C and N released during burning, the following equation was used:

$$\text{C or N released} = \Sigma \text{ for all crop types and states} \left[\frac{\text{AB}}{\text{CAH} \times \text{CP} \times \text{RCR} \times \text{DMF} \times \text{BE} \times \text{CE} \times (\text{FC or FN})} \right]$$

where,

Area Burned (AB) = Total area of crop burned, by state
Crop Area Harvested (CAH) = Total area of crop harvested, by state
Crop Production (CP) = Annual production of crop in kt, by state
Residue:Crop Ratio (RCR) = Amount of residue produced per unit of crop production
Dry Matter Fraction (DMF) = Amount of dry matter per unit of biomass for a crop
Fraction of C or N (FC or FN) = Amount of C or N per unit of dry matter for a crop
Burning Efficiency (BE) = The proportion of prefire fuel biomass consumed[16]
Combustion Efficiency (CE) = The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively

Crop Production and Crop Area Harvested were available by state and year from USDA (2014) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount C or N released was used in the following equation to determine the CH_4, CO, N_2O and NO_x emissions from the field burning of agricultural residues:

$$CH_4 \text{ and CO, or } N_2O \text{ and } NO_x \text{ Emissions from Field Burning of Agricultural Residues} =$$

$$\text{C or N Released} \times \text{ER for C or N} \times \text{CF}$$

where,

Emissions Ratio (ER) = 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), or CO-C to C (28/12), or N_2O-N to N (44/28), or NO_x-N to N (30/14)

Box 5-3: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues were calculated using a Tier 2 methodology that is based on IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach, and not the IPCC (2006) approach, 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; and (3) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory analyzes emissions from seven crops (corn, cotton, lentils, rice, soybeans, sugarcane, and wheat).

A comparison of the methods and factors used in: (1) The current Inventory and (2) the default IPCC (2006) approach was undertaken in the 1990 through 2013 Inventory report to determine the difference in overall estimates between the two approaches. To estimate greenhouse gas emissions from Field Burning of Agricultural Residue using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used:

$$\text{Emissions (kt)} = \text{AB} \times (M_B \times C_f) \times G_{ef} \times 10^{-6}$$

where,

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[16] In IPCC/UNEP/OECD/IEA (1997), the equation for C or N released contains the variable 'fraction oxidized in burning'. This variable is equivalent to (burning efficiency × combustion efficiency).

Area Burned (AB) = Total area of crop burned (ha)
Mass Burned ($M_B \times C_f$) = IPCC (2006) default fuel biomass consumption (metric tons dry matter burnt ha^{-1})
Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

The IPCC (2006) default approach resulted in 5 percent higher emissions of CH_4 and 21 percent higher emissions of N_2O than the estimates in this Inventory (and are within the uncertainty percentage ranges estimated for this source category). It is reasonable to maintain the current methodology, since the IPCC (2006) defaults are only available for four crops and are worldwide average estimates, while current estimates are based on U.S.-specific, crop-specific, published data.

Crop production data for all crops (except rice in Florida and Oklahoma) were taken from USDA's QuickStats service (USDA 2014). Rice production and area data for Florida and Oklahoma were estimated separately as they are not collected by USDA. Average primary and ratoon rice crop yields for Florida (Schueneman and Deren 2002) were applied to Florida acreages (Schueneman 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2014), and rice crop yields for Arkansas (USDA 2014) were applied to Oklahoma acreages[17] (Lee 2003 through 2007; Anderson 2008 through 2014). The production data for the crop types whose residues are burned are presented in Table 5-25. Crop weight by bushel was obtained from Murphy (1993).

The fraction of crop area burned was calculated using data on area burned by crop type and state[18] from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.[19] McCarty (2010) used remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate area burned by crop. State-level area burned data were divided by state-level crop area harvested data to estimate the percent of crop area burned by crop type for each state. The average fraction of area burned by crop type across all states is shown in Table 5-26. As described above, all crop area harvested data were from USDA (2014), except for rice acreage in Florida and Oklahoma, which is not measured by USDA (Schueneman 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2014; Lee 2003 through 2007; Anderson 2008 through 2014). Data on crop area burned were only available from McCarty (2010) for the years 2003 through 2007. For other years in the time series, the percent area burned was set equal to the average five-year percent area burned, based on data availability and inter-annual variability. This average was taken at the crop and state level. Table 5-26 shows these percent area estimates aggregated for the United States as a whole, at the crop level. State-level estimates based on state-level crop area harvested and area burned data were also prepared, but are not presented here.

All residue:crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützle (1987). The ratio for sugarcane is from Kinoshita (1988) and the ratio for cotton is from Huang et al. (2007). The residue:crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry matter fractions were obtained from Strehler and Stützle (1987); the value for lentil residue was assumed to equal the value for bean straw. The cotton dry matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents of cotton are from Lachnicht et al. (2004). These data are listed in Table 5-27. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types, except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). Emission ratios

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[17] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

[18] Alaska and Hawaii were excluded.

[19] McCarty (2009) also examined emissions from burning of Kentucky bluegrass and a general "other crops/fallow" category, but USDA crop area and production data were insufficient to estimate emissions from these crops using the methodology employed in the Inventory. McCarty (2009) estimates that approximately 18 percent of crop residue emissions result from burning of the Kentucky bluegrass and "other crops" categories.

and conversion factors for all gases (see Table 5-28) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 5-25: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2009	2010	2011	2012	2013
Corn[a]	1,534	282,263	332,549	316,165	313,949	273,832	353,715
Cotton	3,376	5,201	2,654	3,942	3,391	3,770	2,811
Lentils	40	238	265	393	215	240	228
Rice	7,114	10,132	9,972	11,027	8,389	9,048	8,613
Soybeans	52,416	83,507	91,417	90,605	84,192	82,055	89,507
Sugarcane	25,525	24,137	27,608	24,821	26,512	29,193	27,906
Wheat	74,292	57,243	60,366	60,062	54,413	61,755	57,961

[a] Corn for grain (i.e., excludes corn for silage).

Table 5-26: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2009	2010	2011	2012	2013
Corn	+	+	+	+	+	+	+
Cotton	1%	1%	1%	1%	1%	1%	1%
Lentils	3%	+	1%	+	1%	1%	1%
Rice	10%	6%	9%	8%	10%	9%	9%
Soybeans	+	+	+	+	+	+	+
Sugarcane	59%	26%	37%	38%	40%	37%	38%
Wheat	3%	2%	3%	3%	3%	3%	3%

+ Less than 0.5 percent

Table 5-27: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue:Crop Ratio	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
Corn	1.0	0.91	0.448	0.006	0.93	0.88
Cotton	1.6	0.90	0.445	0.012	0.93	0.88
Lentils	2.0	0.85	0.450	0.023	0.93	0.88
Rice	1.4	0.91	0.381	0.007	0.93	0.88
Soybeans	2.1	0.87	0.450	0.023	0.93	0.88
Sugarcane	0.2	0.62	0.424	0.004	0.81	0.68
Wheat	1.3	0.93	0.443	0.006	0.93	0.88

Table 5-28: 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).

Uncertainty and Time-Series Consistency

Due to data limitations, uncertainty resulting from the fact that emissions from burning of Kentucky bluegrass and "other crop" residues are not included in the emissions estimates was not incorporated into the uncertainty analysis. The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 5-29. CH_4 emissions from Field Burning of Agricultural Residues in 2013 were estimated to be between 0.2 and 0.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 41 percent below and 42 percent above the 2013 emission estimate of 0.3 MMT CO_2 Eq.[20] Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.07 and 0.14 MMT CO_2 Eq., or approximately 30 percent below and 31 percent above the 2013 emission estimate of 0.10 MMT CO_2 Eq.

Table 5-29: 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	2013 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	0.3	0.2	0.4	-41%	42%
Field Burning of Agricultural Residues	N_2O	0.1	0.1	0.1	-30%	31%

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for Field Burning of Agricultural Residues was implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and crops to attempt to identify any outliers or inconsistencies. For some crops and years in Florida and Oklahoma, the total area burned as measured by McCarty (2010) was greater than the area estimated for that crop, year, and state by Gonzalez (2004–2008) and Lee (2007) for Florida and Oklahoma, respectively, leading to a percent area burned estimate of greater than 100 percent. In such cases, it was assumed that the percent crop area burned for that state was 100 percent.

Recalculations Discussion

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous Inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations Chapter. As a result of the updated GWP values, emission estimates for each year in 1990 through 2012 increased by 19 percent for CH_4 and decreased by 4 percent for N_2O relative to the emission estimates in previous Inventory reports. Rice cultivation data for Florida and

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[20] This value of 0.31 MMT CO_2 is rounded and reported as 0.3 MMT CO_2 in Table 6-21 and the text discussing Table 6-21. For the uncertainty calculations, the value of 0.31 MMT CO_2 was used to allow for more precise uncertainty ranges.

Oklahoma, which are not reported by USDA, were updated for 2013 through communications with state experts (Gonzales 2014, Anderson 2014).

Planned Improvements

Further investigation will be conducted into inconsistent area burned data from Florida and Oklahoma as mentioned in the QA/QC and Verification section, and attempts will be made to revise or further justify the assumption of 100 percent of area burned for those crops and years where the estimated percent area burned exceeds 100 percent. The availability of useable area harvested and other data for Kentucky bluegrass and the “other crops” category in McCarty (2010) will also be investigated in order to try to incorporate these emissions into past and future estimates. More crop area burned data and new data to estimate crop-specific burning efficiency and consumption efficiency, and emissions are becoming available—e.g., the combustion completeness and emission factors used for the EPA National Emissions Inventory (NEI)[21]—and will be analyzed for incorporation into future Inventory reports.

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[21] More information on the NEI is available online at: <http://www.epa.gov/ttn/chief/net/2014inventory.html>

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux resulting from the uses and changes in land types and forests in the United States.[1] The Intergovernmental Panel on Climate Change *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between certain land-use types termed: Forest Land, Cropland, Grassland, Settlements, Wetlands (as well as Other Land). The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest carbon (C) stocks, non-carbon dioxide (non-CO_2) emissions from forest fires, and the application of synthetic fertilizers to forest soils. The greenhouse gas flux from agricultural lands (i.e., Cropland and Grassland) that is reported in this chapter includes changes in organic C stocks in mineral and organic soils due to land use and management, and emissions of CO_2 due to the application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization. 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*. Fluxes resulting from *Settlements Remaining Settlements* include those from urban trees and soil fertilization. Landfilled yard trimmings and food scraps are accounted for separately under *Other*.

The estimates in this chapter, with the exception of CO_2 removals from harvested wood products and urban trees, and CO_2 emissions from liming and urea fertilization, are based on activity data collected at multiple-year intervals, which are in the form of forest, land use, and municipal solid waste surveys. Carbon dioxide fluxes from forest C stocks (except the harvested wood product components) and from agricultural soils (except the liming component) are calculated on an average annual basis from data collected in intervals ranging from one to 10 years. The resulting annual averages are applied to years between surveys. Calculations of non-CO_2 emissions from forest fires are based on forest CO_2 flux data. For the landfilled yard trimmings and food scraps source, historical annual solid waste survey data were interpolated where annual data were missing so that annual storage estimates could be derived. This flux has been applied to the entire time series, and periodic U.S. census data on changes in urban area have been used to develop annual estimates of CO_2 flux.

Land use, land-use change, and forestry activities in 2013 resulted in a C sequestration (i.e., total sinks) of 881.7 MMT CO_2 Eq.[2] (240.5 MMT C).[3] This represents an offset of approximately 13.2 percent of total (i.e., gross)

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[1] The term "flux" is used to describe the net emissions of greenhouse gases to the atmosphere accounting for both the emissions of CO_2 to and the removals of CO_2 from the atmosphere. Removal of CO_2 from the atmosphere is also referred to as "carbon sequestration".

[2] Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

[3] The total sinks value includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland.*

greenhouse gas emissions in 2013. Emissions from land use, land-use change, and forestry activities in 2013 represent 0.3 percent of total greenhouse gas emissions.[4]

Total land use, land-use change, and forestry C sequestration increased by approximately 13.6 percent between 1990 and 2013. This increase was primarily due to an increase in the rate of net C accumulation in forest C stocks.[5] Net C accumulation in *Forest Land Remaining Forest Land, Land Converted to Grassland*, and *Settlements Remaining Settlements* increased, while net C accumulation in *Cropland Remaining Cropland, Grassland Remaining Grassland*, and *Landfilled Yard Trimmings and Food Scraps* slowed over this period. Emissions from *Land Converted to Cropland* and *Wetlands Remaining Wetlands* decreased. Emissions and removals for Land Use, Land-Use Change, and Forestry are summarized in Table 6-1 by land-use and source category.

Table 6-1: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry by Land-Use Change Category (MMT CO_2 Eq.)

Land-Use/Source Category	1990	2005	2009	2010	2011	2012	2013
Forest Land Remaining Forest Land	**(635.2)**	**(792.9)**	**(754.7)**	**(757.1)**	**(749.2)**	**(746.7)**	**(765.5)**
Changes in Forest Carbon Stock[a]	(639.4)	(807.1)	(764.9)	(765.4)	(773.8)	(773.1)	(775.7)
Forest Fires	4.2	13.8	9.7	7.9	24.2	26.0	9.7
Forest Soils[b]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Cropland Remaining Cropland	**(58.1)**	**(20.2)**	**(20.2)**	**(17.3)**	**(17.8)**	**(15.0)**	**(13.5)**
Changes in Agricultural Soil Carbon Stock	(65.2)	(28.0)	(27.5)	(25.9)	(25.8)	(25.0)	(23.4)
Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Land Converted to Cropland	**24.5**	**19.8**	**16.2**	**16.2**	**16.2**	**16.1**	**16.1**
Changes in Agricultural Soil Carbon Stock	24.5	19.8	16.2	16.2	16.2	16.1	16.1
Grassland Remaining Grassland	**(1.9)**	**4.2**	**11.7**	**11.7**	**11.7**	**11.5**	**12.1**
Changes in Agricultural Soil Carbon Stock	(1.9)	4.2	11.7	11.7	11.7	11.5	12.1
Land Converted to Grassland	**(7.4)**	**(9.0)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.8)**	**(8.8)**
Changes in Agricultural Soil Carbon Stock	(7.4)	(9.0)	(8.9)	(8.9)	(8.9)	(8.8)	(8.8)
Settlements Remaining Settlements	**(59.0)**	**(78.2)**	**(82.8)**	**(83.8)**	**(84.8)**	**(85.8)**	**(87.1)**
Changes in Urban Tree Carbon Stock[c]	(60.4)	(80.5)	(85.0)	(86.1)	(87.3)	(88.4)	(89.5)
Settlement Soils[d]	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Wetlands Remaining Wetlands	**1.1**	**1.1**	**1.0**	**1.0**	**0.9**	**0.8**	**0.8**
Peatlands Remaining Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8
Other	**(26.0)**	**(11.4)**	**(12.5)**	**(13.2)**	**(13.2)**	**(12.8)**	**(12.6)**
Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(12.5)	(13.2)	(13.2)	(12.8)	(12.6)
Total Flux[e]	**(762.1)**	**(886.4)**	**(850.2)**	**(851.3)**	**(844.9)**	**(840.6)**	**(858.5)**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[c] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[d] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

[e] "Total Flux" is defined as the sum of positive emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

CO_2 removals are presented in Table 6-2 along with CO_2, CH_4, and N_2O emissions from Land use, Land-Use Change, and Forestry source categories. Liming of agricultural soils and urea fertilization in 2013 resulted in CO_2 emissions of 9.9 MMT CO_2 Eq. (9,936 kt). Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*)

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[4] The emissions value includes the CO_2, CH_4, and N_2O emissions reported for *Forest Fires, Forest Soils, Liming of Agricultural Soils, Urea Fertilization, Settlement Soils*, and *Peatlands Remaining Peatlands*.

[5] Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink; also referred to as net C sequestration or removal.

resulted in CO_2 emissions of 0.8 MMT CO_2 Eq. (770 kt), methane (CH_4) emissions of less than 0.05 MMT CO_2 Eq., and nitrous oxide (N_2O) emissions of less than 0.05 MMT CO_2 Eq. The application of synthetic fertilizers to forest soils in 2013 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt). N_2O emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions. Additionally, N_2O emissions from fertilizer application to settlement soils in 2013 accounted for 2.4 MMT CO_2 Eq. (8 kt). This represents an increase of 77 percent since 1990. Forest fires in 2013 resulted in CH_4 emissions of 5.8 MMT CO_2 Eq. (233 kt), and in N_2O emissions of 3.8 MMT CO_2 Eq. (13 kt). Emissions and removals for Land Use, Land-Use Change, and Forestry are shown in Table 6-2 and Table 6-3.

Table 6-2: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2009	2010	2011	2012	2013
CO_2	**(767.7)**	**(903.0)**	**(862.6)**	**(862.0)**	**(872.1)**	**(869.6)**	**(871.0)**
Forest Land Remaining Forest Land: Changes in Forest Carbon Stock[a]	(639.4)	(807.1)	(764.9)	(765.4)	(773.8)	(773.1)	(775.7)
Cropland Remaining Cropland: Changes in Agricultural Soil Carbon Stock	(65.2)	(28.0)	(27.5)	(25.9)	(25.8)	(25.0)	(23.4)
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.3	3.7	4.8	3.9	5.8	5.9
Cropland Remaining Cropland: Urea Fertilization	2.4	3.5	3.6	3.8	4.1	4.2	4.0
Land Converted to Cropland	24.5	19.8	16.2	16.2	16.2	16.1	16.1
Grassland Remaining Grassland	(1.9)	4.2	11.7	11.7	11.7	11.5	12.1
Land Converted to Grassland	(7.4)	(9.0)	(8.9)	(8.9)	(8.9)	(8.8)	(8.8)
Settlements Remaining Settlements: Changes in Urban Tree Carbon Stock[b]	(60.4)	(80.5)	(85.0)	(86.1)	(87.3)	(88.4)	(89.5)
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.1	1.1	1.0	1.0	0.9	0.8	0.8
Other: Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(12.5)	(13.2)	(13.2)	(12.8)	(12.6)
CH_4	**2.5**	**8.3**	**5.8**	**4.8**	**14.6**	**15.7**	**5.8**
Forest Land Remaining Forest Land: Forest Fires	2.5	8.3	5.8	4.7	14.6	15.7	5.8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**3.1**	**8.3**	**6.5**	**6.0**	**12.6**	**13.3**	**6.7**
Forest Land Remaining Forest Land: Forest Fires	1.7	5.5	3.8	3.1	9.6	10.3	3.8
Forest Land Remaining Forest Land: Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Settlements Remaining Settlements: Settlement Soils[d]	1.4	2.3	2.2	2.4	2.5	2.5	2.4
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total Flux[e]	**(762.1)**	**(886.4)**	**(850.2)**	**(851.3)**	**(844.9)**	**(840.6)**	**(858.5)**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Less than 0.05 MMT CO_2 Eq.

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[d] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion

[e] "Total Flux" is defined as the sum of positive emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO_2 (i.e., sinks or negative emissions) from the atmosphere.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-3: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry (kt)

Gas/Land-Use Category	1990	2005	2009	2010	2011	2012	2013
CO_2	**(767,697)**	**(902,974)**	**(862,631)**	**(862,025)**	**(872,103)**	**(869,580)**	**(871,026)**
Forest Land Remaining Forest Land: Changes in Forest Carbon Stock[a]	(639,432)	(807,075)	(764,871)	(765,410)	(773,843)	(773,110)	(775,677)
Cropland Remaining Cropland: Changes in Agricultural Soil Carbon Stock	(65,196)	(28,035)	(27,473)	(25,867)	(25,752)	(24,990)	(23,432)
Cropland Remaining Cropland: Liming of Agricultural Soils	4,667	4,349	3,669	4,784	3,871	5,776	5,925
Cropland Remaining Cropland: Urea Fertilization	2,417	3,504	3,555	3,778	4,099	4,225	4,011
Land Converted to Cropland	24,498	19,830	16,194	16,194	16,194	16,095	16,125
Grassland Remaining Grassland	(1,913)	4,230	11,704	11,694	11,680	11,532	12,083
Land Converted to Grassland	(7,410)	(8,995)	(8,917)	(8,894)	(8,871)	(8,783)	(8,757)
Settlements Remaining Settlements: Changes in Urban Tree Carbon Stock[b]	(60,408)	(80,523)	(85,008)	(86,129)	(87,250)	(88,372)	(89,493)
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1,055	1,101	1,024	1,022	926	812	770
Other: Landfilled Yard Trimmings and Food Scraps	(25,975)	(11,360)	(12,508)	(13,197)	(13,156)	(12,766)	(12,581)
CH_4	**101**	**332**	**234**	**190**	**584**	**627**	**233**
Forest Land Remaining Forest Land: Forest Fires	101	332	233	190	584	626	233
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N_2O	**10**	**28**	**22**	**20**	**42**	**45**	**23**
Forest Land Remaining Forest Land: Forest Fires	6	18	13	11	32	35	13
Forest Land Remaining Forest Land: Forest Soils[c]	+	2	2	2	2	2	2
Settlements Remaining Settlements: Settlement Soils[d]	5	8	8	8	8	8	8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+

\+ Emissions are less than 0.5 kt

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

[d] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions 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 Intergovernmental Panel on Climate Change

(IPCC).[6] Additionally, the calculated emissions and sinks in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[7] The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

6.1 Representation of the U.S. Land Base

A national land-use categorization 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 (GHG) fluxes over the Inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national GHG fluxes to the UNFCCC should: (1) Describe the methods and definitions used to determine areas of managed and unmanaged lands in the country, (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), and (3) account for GHG fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic GHG 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 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 GHG emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. Guidelines for factoring out natural emissions and removals may be developed in the future, but currently the managed land proxy is considered the most practical approach for conducting an inventory in this sector (IPCC 2010). The implementation of such a system helps to ensure that estimates of GHG fluxes are as accurate as possible, and does allow for potentially subjective decisions in regards to subdividing natural and anthropogenic driven emissions. This section of the Inventory has been developed in order to comply with this guidance.

Three databases are used to track land management in the United States and are used as the basis to classify U.S. land area into the thirty-six IPCC land-use and land-use change categories (Table 6-5) (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)[8] and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[9] Database. The Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD)[10] is also used to identify land uses in regions that were not included in the NRI or FIA.

The total land area included in the U.S. Inventory is 936 million hectares across the 50 states.[11] Approximately 890 million hectares of this land base is considered managed, which has not changed by much over the time series of the

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

[7] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

[8] NRI data is available at <http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>.

[9] FIA data is available at <http://www.fia.fs.fed.us/tools-data/default.asp>.

[10] NLCD data is available at <http://www.mrlc.gov/> and MRLC is a consortium of several U.S. government agencies.

[11] The current land representation does not include areas from U.S. territories, but there are planned improvements to include these regions in future reports.

Inventory (Table 6-5). In 2013, the United States had a total of 293 million hectares of managed Forest Land (1.3 percent increase since 1990), 159 million hectares of Cropland (6.6 percent decrease since 1990), 321 million hectares of managed Grassland (1.1 percent decrease since 1990), 43 million hectares of managed Wetlands (3 percent decrease since 1990), 51 million hectares of Settlements (31 percent increase since 1990), and 24 million hectares of managed Other Land (Table 6-5). Wetlands are not differentiated between managed and unmanaged, and are reported solely as managed. Some wetlands would be considered unmanaged, and a future planned improvement will include a differentiation between managed and unmanaged wetlands using guidance in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands*. In addition, C 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 (e.g., Grassland Remaining Grassland).[12,13] Planned improvements are under development to account for C stock changes on all managed land (e.g., federal grasslands) and 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 patterns, although all land uses occur within each of the 50 states (Table 6-4). Forest Land tends to be more common in the eastern 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 Midwest and eastern portions of the country. 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	2009	2010	2011	2012	2013
Managed Lands	**890,018**	**890,016**	**890,016**	**890,017**	**890,017**	**890,017**	**890,017**
Forest Land	288,964	291,213	292,263	292,399	292,516	292,634	292,751
Croplands	170,448	160,107	159,248	159,243	159,238	159,234	159,230
Grasslands	324,327	321,360	320,666	320,657	320,655	320,652	320,648
Settlements	38,602	49,676	50,628	50,624	50,621	50,617	50,614
Wetlands	44,453	44,060	43,441	43,330	43,228	43,126	43,025
Other Land	23,225	23,600	23,770	23,765	23,759	23,754	23,748
Unmanaged Lands	**46,212**	**46,214**	**46,214**	**46,213**	**46,213**	**46,214**	**46,214**
Forest Land	9,634	9,634	9,634	9,634	9,634	9,634	9,634
Croplands	0	0	0	0	0	0	0
Grasslands	25,782	25,782	25,782	25,782	25,782	25,782	25,782
Settlements	0	0	0	0	0	0	0
Wetlands	0	0	0	0	0	0	0
Other Land	10,796	10,798	10,798	10,797	10,797	10,797	10,797
Total Land Areas	**936,230**	**936,230**	**936,230**	**936,230**	**936,230**	**936,230**	**936,230**
Forest Land	298,598	300,848	301,898	302,033	302,151	302,268	302,386
Croplands	170,448	160,107	159,248	159,243	159,238	159,234	159,230
Grasslands	350,109	347,142	346,448	346,439	346,437	346,434	346,430
Settlements	38,602	49,676	50,628	50,624	50,621	50,617	50,614
Wetlands	44,453	44,060	43,441	43,330	43,228	43,126	43,025
Other Land	34,021	34,397	34,568	34,562	34,556	34,551	34,545

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[12] C stock changes are not estimated for approximately 75 million hectares of Grassland Remaining Grassland. See specific land-use sections for further discussion on gaps in the inventory of C stock changes, and discussion about planned improvements to address the gaps in the near future.

[13] These "managed area" discrepancies also occur in the Common Reporting Format (CRF) tables submitted to the UNFCCC.

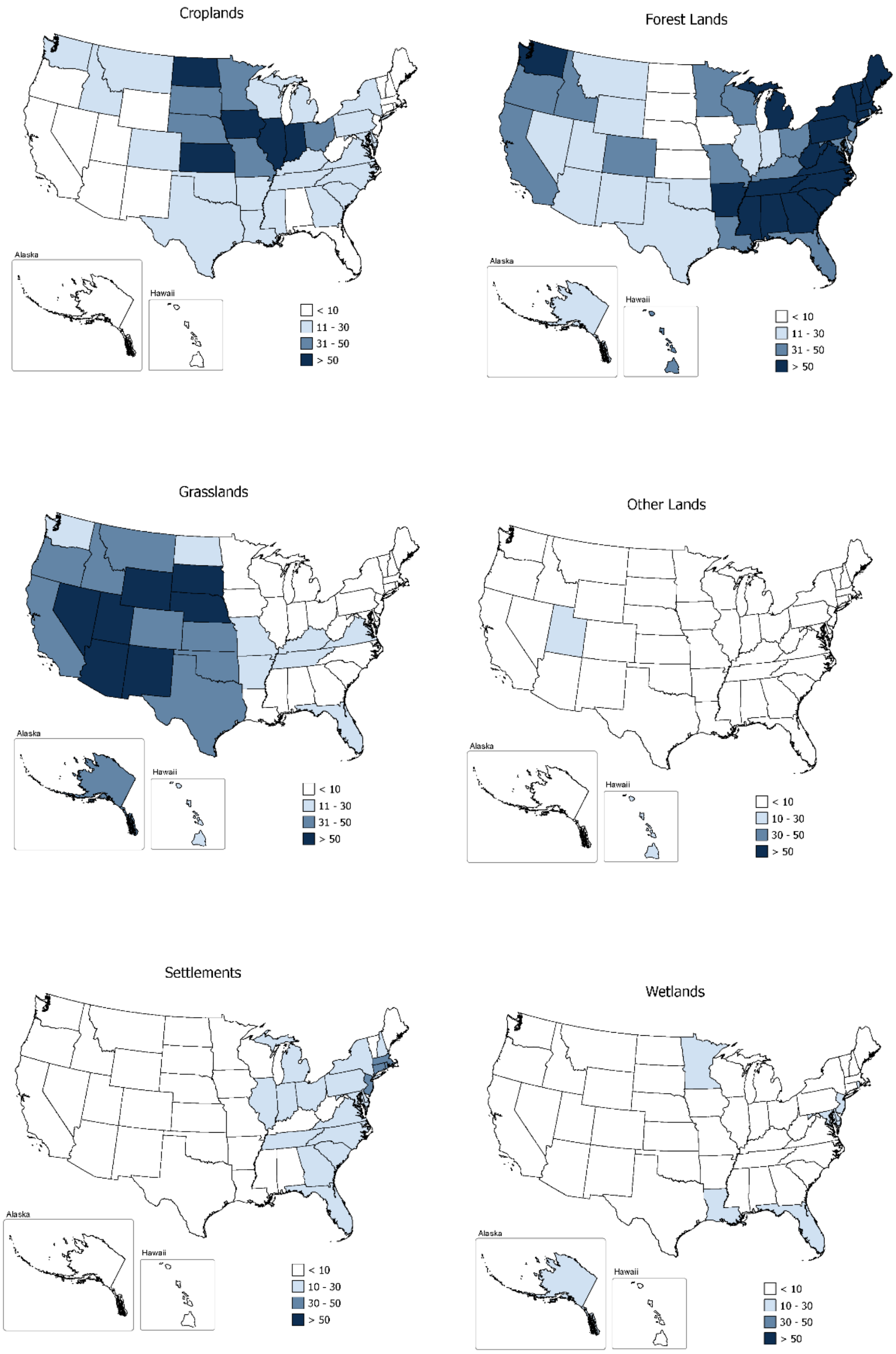
Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land-Use & Land-Use Change Categories[a]	1990	2005	2009	2010	2011	2012	2013
Total Forest Land	**288,964**	**291,213**	**292,263**	**292,399**	**292,516**	**292,634**	**292,751**
FF	283,860	278,979	280,844	280,977	281,092	281,207	281,322
CF	1,119	2,656	2,449	2,450	2,450	2,450	2,450
GF	3,434	7,805	7,279	7,280	7,280	7,281	7,281
WF	64	250	257	257	258	258	259
SF	103	362	376	376	376	377	377
OF	383	1,161	1,057	1,059	1,060	1,062	1,063
Total Cropland	**170,448**	**160,107**	**159,248**	**159,243**	**159,238**	**159,234**	**159,230**
CC	154,527	143,050	143,933	143,928	143,924	143,920	143,916
FC	1,148	688	577	576	576	576	576
GC	13,988	15,216	13,655	13,655	13,655	13,655	13,655
WC	161	199	176	176	176	175	175
SC	438	692	672	672	672	672	672
OC	185	262	236	236	236	236	236
Total Grassland	**324,327**	**321,360**	**320,666**	**320,657**	**320,655**	**320,652**	**320,648**
GG	313,914	301,823	302,566	302,594	302,627	302,660	302,692
FG	1,615	3,022	2,757	2,755	2,753	2,752	2,750
CG	8,099	14,986	13,912	13,878	13,844	13,810	13,776
WG	238	409	330	329	329	329	329
SG	112	274	267	267	267	267	267
OG	350	846	834	834	834	834	834
Total Wetlands	**44,453**	**44,060**	**43,441**	**43,330**	**43,228**	**43,126**	**43,025**
WW	43,802	42,545	42,002	41,892	41,792	41,691	41,592
FW	143	397	382	381	380	379	378
CW	132	365	345	345	344	344	344
GW	343	698	664	664	664	664	664
SW	0	10	10	10	10	10	10
OW	32	44	39	39	38	38	38
Total Settlements	**38,602**	**49,676**	**50,628**	**50,624**	**50,621**	**50,617**	**50,614**
SS	34,060	35,269	36,340	36,337	36,334	36,330	36,328
FS	1,787	6,112	6,090	6,090	6,090	6,090	6,089
CS	1,344	3,633	3,526	3,526	3,526	3,526	3,526
GS	1,353	4,433	4,439	4,439	4,439	4,439	4,439
WS	3	31	30	30	30	30	30
OS	55	200	202	202	202	202	202
Total Other Land	**23,225**	**23,600**	**23,770**	**23,765**	**23,759**	**23,754**	**23,748**
OO	22,175	21,372	21,470	21,466	21,460	21,455	21,450
FO	182	538	569	569	569	570	570
CO	345	645	703	703	703	703	703
GO	454	903	902	902	902	901	901
WO	67	121	104	104	104	104	104
SO	2	21	20	20	20	20	20
Grand Total	**890,018**	**890,016**	**890,016**	**890,017**	**890,017**	**890,017**	**890,017**

[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).

Note: 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 territories in future inventories. In addition, C 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.

Figure 6-1: Percent of Total Land Area for Each State in the General Land-Use Categories for 2013



Methodology

IPCC Approaches for Representing Land Areas

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 changes of area between categories 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 to Cropland, Cropland to Forest Land, and Grassland to Cropland), using survey samples or other forms of data, but does not provide location data on all parcels of land. Approach 3 extends Approach 2 by providing location data on all parcels of land, such as maps, along with the land-use history. 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 and FIA are Approach 2 data sources that do not provide spatially-explicit representations of land use and land-use conversions, even though land use and land-use conversions are tracked explicitly at the survey locations. NRI and FIA data can only be aggregated and used to develop a land-use conversion matrix for a political or ecologically-defined region. NLCD is a spatially-explicit time series of land-cover data that is used to inform the classification of land use, and is therefore Approach 3 data. 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. 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 basic IPCC (2006) definition of managed land, 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

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[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 is difficult due to limited data availability. Wetlands are not characterized by use within the NRI. Therefore, unless wetlands are managed for 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, all wetlands are reported as managed. See the Planned Improvements section of the Inventory for work being done to refine 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 C stocks.

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,[16] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[17] 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 10 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 meters) 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 10 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 meters) wide or an acre (0.4 hectare) in size. Forest Land does not include land that is predominantly under agricultural or urban land use (Oswalt et al. 2014).
- *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.[18] Cultivated crops include row crops or close-grown crops and also hay or 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. Lands in temporary fallow or 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.[21] This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Savannas, some wetlands and deserts, in

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[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] See <http://socrates.lv-hrc.nevada.edu/fia/ab/issues/pending/glossary/Glossary_5_30_06.pdf>.

[17] See <http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>.

[18] A minor portion of Cropland occurs on federal lands, and is not currently included in the C stock change inventory. A planned improvement is underway to include these areas in future C inventories.

[19] Currently, there is no data source to account for biomass C 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.

[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.

[21] Grasslands on federal lands are included in the managed land base, but C stock changes are not estimated on these lands. Federal grassland areas have been assumed to have negligible changes in C due to limited land-use and management change, but planned improvements are underway to further investigate this issue and include these areas in future C inventories.

addition to tundra are considered Grassland.[22] Woody plant communities of low forbs and shrubs, such as mesquite, chaparral, mountain shrub, 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 silvipasture and windbreaks, if the land is principally grasses, 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 the areas of lakes, reservoirs, and rivers. Managed Wetlands are those where the water level is artificially changed, or 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, including Cropland (drained wetlands for crop production and also systems that are flooded for most or just part of the year, such as rice cultivation and cranberry production), Grassland (drained wetlands dominated by grass cover), and Forest Land (including drained or un-drained forested wetlands).
- *Settlements*: A land-use category representing developed areas consisting of units of 0.25 acres (0.1 ha) or more 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 tracts of less than 10 acres (4.05 ha) that may meet the definitions for Forest Land, 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, which allows the total of identified land areas to match the managed land base. Following the guidance provided by the IPCC (2006), C stock changes are not estimated for Other Lands because these areas are largely devoid of biomass, litter and soil C pools.

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 the surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data from which to estimate C stock changes 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.

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		•	

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[22] IPCC (2006) guidelines do not include provisions to separate desert and tundra as land categories.

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 on all land uses on non-federal lands in the conterminous United States and Hawaii (except Forest Land), and is also used as the resource 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 hectare] 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 derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands and grasslands, and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 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 has 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 2007 from the NRI.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is another statistically-based survey for the conterminous United States, and the official source of data on Forest Land area and management data for the Inventory in this region of the country. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs 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 C 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 14 years. A new national plot design and annual sampling design was introduced by FIA about ten years ago. Most states, though, have only recently been brought into this system. 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 years. See Annex

3.13 to see 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 2012 through 2013; see Table A-246).

National Land Cover Dataset

Though NRI provides land-area data for both federal and non-federal lands in the conterminous United States and Hawaii, it only includes land-use data on non-federal lands, and FIA only records data for forest land.[23] Consequently, major gaps exist when the datasets are combined, such as federal grassland operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[24] The NLCD is used as a supplementary database to account for land use on federal lands that are not included in the NRI and FIA databases. The NLCD land-cover classification scheme, available for 1992, 2001, 2006, and 2011 has been applied over the conterminous United States (Homer et al. 2007), and also for Alaska and Hawaii in 2001. For the conterminous United States, the NLCD Land Cover Change Products for 2001, 2006, and 2011 were used in order to represent both land use and land-use change for federal lands (Fry et al. 2011, Homer et al. 2007, Jin et al. 2013). The NLCD products are based primarily on Landsat Thematic Mapper imagery. The NLCD contains 21 categories of land-cover information, which have been aggregated into the IPCC land-use categories, and the data are available at a spatial resolution of 30 meters. The federal land portion of the NLCD was extracted from the dataset using the federal land area boundary map from the National Atlas (U.S. Department of Interior 2005). This map represents federal land boundaries in 2005, so as part of the analysis, the federal land area was adjusted annually based on the NRI federal land area estimates (i.e., land is periodically transferred between federal and non-federal ownership). Consequently, the portion of the land base categorized with NLCD data varied from year to year, corresponding to an increase or decrease in the federal land base. The NLCD is strictly a source of land-cover information, however, and does not provide the necessary site conditions, crop types, and management information from which to estimate C stock changes on those lands.

As part of Quality Assurance and Quality Control (QA/QC), the land base derived from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) survey (U.S. Census Bureau 2010). The U.S. Census Bureau gathers data on the U.S. population and economy, and has a database of land areas for the country. The land area estimates from the U.S. Census Bureau differ from those provided by the land-use surveys used in the Inventory because of discrepancies in the reporting approach for the Census and the methods used in the NRI, FIA, and NLCD. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the U.S. Census Survey. More importantly, the U.S. Census Survey does not provide a time series of land-use change data or land management information. Consequently, the U.S. Census Survey was not adopted as the official land area estimate for the Inventory. Rather, the NRI, FIA, and NLCD datasets were adopted because this database provides full coverage of land area and land use for the conterminous United States, Alaska, and Hawaii, in addition to management and other data relevant for the Inventory. Regardless, the total difference between the U.S. Census Survey and the combined NRI, FIA, and NLCD data is about 22 million hectares for the total U.S. land base of about 936 million hectares currently included in the Inventory, or a 2.4 percent difference. Much of this difference is associated with open waters in coastal regions and the Great Lakes, which is included in the Census.

Managed Land Designation

Lands are designated as managed in the United States based on the definitions provided earlier in this section. In order to apply the definitions in an analysis of managed land, the following criteria are used:

- All Croplands and Settlements are designated as managed so only Grassland, Forest Land or Other Lands may be designated as unmanaged land;[25]
- All Forest Land with active fire protection are considered managed;

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[23] FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[24] The FIA and NRI survey programs also do not include U.S. Territories with the exception of non-federal lands in Puerto Rico, which are included in the NRI survey. Furthermore, NLCD does not include coverage for all U.S. Territories.

[25] A planned improvement is underway to deal with an exception for Wetlands which includes both managed and unmanaged lands based on the definitions for the current U.S. Land Representation Assessment.

- All Grassland is considered managed at a county scale if there are livestock in the county;[26] 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 (managed by public and 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 C stocks.

The analysis of managed lands is conducted using a geographic information system. Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011, Homer et al. 2007, Jin et al. 2013). 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. The designation of grasslands as managed is determined based on USDA National Agricultural Statistics Service livestock population data at the county scale (U.S. Department of Agriculture 2011). 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). However, protected areas that are 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 assumed around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. 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. The remaining land represents the unmanaged land base.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the thirty-six IPCC land-use categories using definitions developed to meet national circumstances, while adhering to IPCC (2006).[27] In practice, the land was initially classified into a variety of land-use categories within the NRI, FIA, and NLCD datasets, and then aggregated into the thirty-six 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 estimating Forest Land use areas in the conterminous United States.

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. In addition, dependence exists between the Forest Land area and the amount of land designated as other land uses in both the NRI and the NLCD, such as the amount of Grassland, Cropland, and Wetlands, relative to the Forest Land area. This results in inconsistencies among the three databases for estimated Forest Land area, as well as for the area estimates for other land-use categories. FIA is the main database for forest statistics, and consequently, the NRI and NLCD were adjusted to achieve consistency with FIA estimates of Forest Land in the conterminous United States. The adjustments were made at a state-scale, and it was assumed that the majority of the discrepancy in forest area was associated with an under- or over-prediction of

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[26] Assuming all grasslands are grazed in a county with livestock is a conservation assumption about human impacts on grasslands. Currently, detailed information on grazing at sub-county scales is not available for the United States to make a finer delineation of managed land.

[27] Definitions are provided in the previous section.

Grassland and Wetland area in the NRI and NLCD due to differences in forest land definitions. Specifically, the forest land area for a given state according to the NRI and NLCD was adjusted to match the FIA estimates of Forest Land for non-federal and federal land in *Forest Lands Remaining Forest Lands*, respectively. In a second step, corresponding increases or decreases were made in the area estimates of Grassland and Wetland from the NRI and NLCD, *Grasslands Remaining Grasslands* and *Wetlands Remaining Wetlands*, in order to balance the change in forest area, and therefore not change the overall amount of managed land within an individual state. The adjustments were based on the proportion of land within each of these land-use categories at the state level. (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 solely on the NLCD data (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.[28]

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Both non-federal and federal forest lands in both the continental United States and coastal Alaska are covered by FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land. Interior Alaska is not currently surveyed by FIA so forest land in Alaska is evaluated with 2001 NLCD. NRI is being used in the current report to provide Forest Land areas on non-federal lands in Hawaii, but FIA data will be collected in Hawaii in the future.
- *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. NRI is used as the basis for both Cropland area data as well as to estimate soil C stocks and fluxes on Cropland. NLCD 2001 is used to determine Cropland area in Alaska.
- *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. NRI is used as the basis for both Grassland area data as well as to estimate soil C stocks and fluxes on Grassland. Grassland on federal Bureau of Land Management lands, Department of Defense lands, National Parks, and within USFS lands are covered by the NLCD. NLCD is used to estimate the areas of federal and non-federal grasslands in Alaska.
- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while federal wetlands and wetlands in Alaska are covered by the NLCD. This currently includes both managed and unmanaged wetlands as no database has yet been applied to make this distinction. See the Planned Improvements section for details.
- *Settlements*: NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 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 10 acre (4.05 ha) threshold and are Grassland, they will be classified as such by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Settlements on federal lands and in Alaska are covered by NLCD.
- *Other Land*: Any land not falling into the other five land-use categories and, therefore, categorized as Other Land is classified using the NRI for non-federal areas in the 49 states (excluding Alaska) and NLCD for the federal lands and 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, in the following manner:

Settlements > *Cropland* > *Forest Land* > *Grassland* > *Wetlands* > *Other Land*

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[28] Only one year of data are currently available for Alaska so there is no information on land-use change for this state.

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 will be 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 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) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands then Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting GHG emissions and removals on managed land, but is intended to classify all areas into a discrete land use. 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 cranberries, 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 from these areas are included in the Inventory if the land is considered managed and presumably impacted by anthropogenic activity in accordance with the guidance provided in IPCC (2006).

Recalculations Discussion

Relative to the previous Inventory, new data were incorporated from FIA on forestland areas, which were used to make minor adjustments to the time series. The managed land base was further refined this year with the new implementation criteria incorporating lands protected for recreation in addition to lands with mineral and petroleum extraction. This change increased the managed land base in Alaska, but had limited impact on the managed land base in the conterminous United States.

Planned Improvements

A key planned improvement is to fully incorporate area data by land-use type for U.S. Territories into the Inventory. Fortunately, most of the managed land in the United States is included in the current land-use statistics, but a complete accounting is a key goal for the near future. Preliminary land-use area data by land-use category are provided in Box 6-2: Preliminary Estimates of Land Use in U.S. Territories for the U.S. Territories.

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, USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program. Land-cover data can be used to inform a land-use classification if there is a time series to evaluate the dominate 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 Coastal Change Analysis Program (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 an 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. The final selection of a land-cover product for these Territories is still under discussion. 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.

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**

Additional work will be conducted to reconcile differences in Forest Land estimates between the NRI and FIA, evaluating the assumption that the majority of discrepancies in Forest Land areas are associated with an over- or under-estimation of Grassland and Wetland area. In some regions of the United States, a discrepancy in Forest Land areas between NRI and FIA may be associated with an over- or under-prediction of other land uses. This improvement would include an analysis designed to develop region-specific adjustments.

There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990, 2000, and 2010 U.S. Census data). Using the population statistics, “urban clusters” are defined as areas with more than 500 people per square mile. The USFS is currently moving ahead with an urban forest inventory program so that urban forest area estimates will be consistent with FIA forest area estimates outside of urban areas, which would be expected to reduce omissions and overlap of forest area estimates along urban boundary areas.

As adopted by the UNFCCC, new guidance in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* will be implemented in the Inventory. This will likely have implications for the classification of managed and unmanaged wetlands in the Inventory report. More detailed wetlands datasets will also be evaluated and integrated into the analysis in order to implement the new guidance.

6.2 Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 4A1)

For estimating carbon (C) stocks or stock change (flux), C 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 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 the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 cm at transect intersection, lying on the ground.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the aboveground pools.

In addition, there are two harvested wood pools to account for when estimating C flux:

- Harvested wood products (HWP) in use.

- HWP in solid waste disposal sites (SWDS).

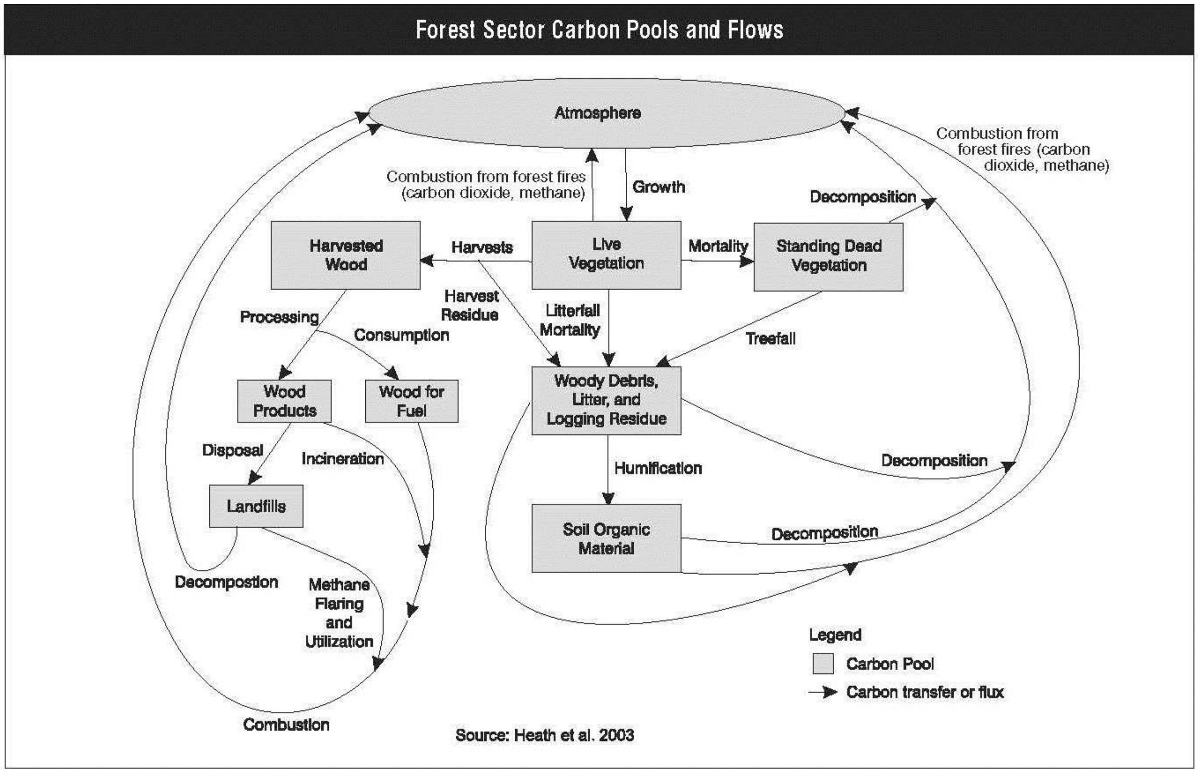
Carbon is continuously cycled among these storage pools and between forest ecosystems and the atmosphere as a result of biological processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere and also is transferred to the soil by organisms that facilitate decomposition.

The net change in forest C 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 C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO_2 when the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately, and these emissions are reported for information purposes in the Energy Sector with the harvest (i.e., the associated reduction in forest carbon stocks) and subsequent combustion implicitly accounted for under the Land Use, Land-Use Change (LULUCF) Sector (i.e., the harvested timber 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 C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the SWDS. These latter fluxes are also accounted for under the LULUCF Sector.

This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The basic methodology for determining C stock and stock-change relies on data from the extensive inventories of U.S. forest lands, and improvements in these inventories over time are reflected in the estimates (Heath et al. 2011, Heath 2012). The net change in stocks for each pool is estimated, and then the changes in stocks are summed for all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Changes in C stocks from disturbances, such as forest fires, are implicitly included in the net changes. For instance, an inventory conducted after fire counts only the trees that are left. Therefore, changes in C stocks from natural disturbances, such as wildfires, pest outbreaks, and storms, are implicitly accounted for in the forest inventory approach; however, they are highly variable from year to year. Wildfire events are typically the most severe but other natural disturbance events can result in large C stock losses that are time- and location- specific. The IPCC (2006) recommends reporting changes in C stocks from forest lands according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Research is ongoing to track C across a matrix of land-uses and land-use changes. Until such time that reliable and comprehensive estimates of C across the land-use matrix can be produced, net changes in all forest-related land, including non-forest land converted to forest and forests converted to non-forest, are reported here in the *Forest Land Remaining Forest Land* Sector (see the Planned Improvements section for more details).

Forest C storage pools, and the flows between them via emissions, sequestration, and transfers, are shown in Figure 6-2. In the figure, boxes represent forest C storage pools and arrows represent flows between storage pools or between storage pools and the atmosphere. Note that the boxes are not identical to the five storage pools identified in the *2006 IPCC Guidelines*. Instead, the storage pools identified have been refined in this graphic to better illustrate the processes that result in transfers of C from one pool to another, and emissions to as well as uptake from the atmosphere.

Figure 6-2: Forest Sector C Pools and Flows



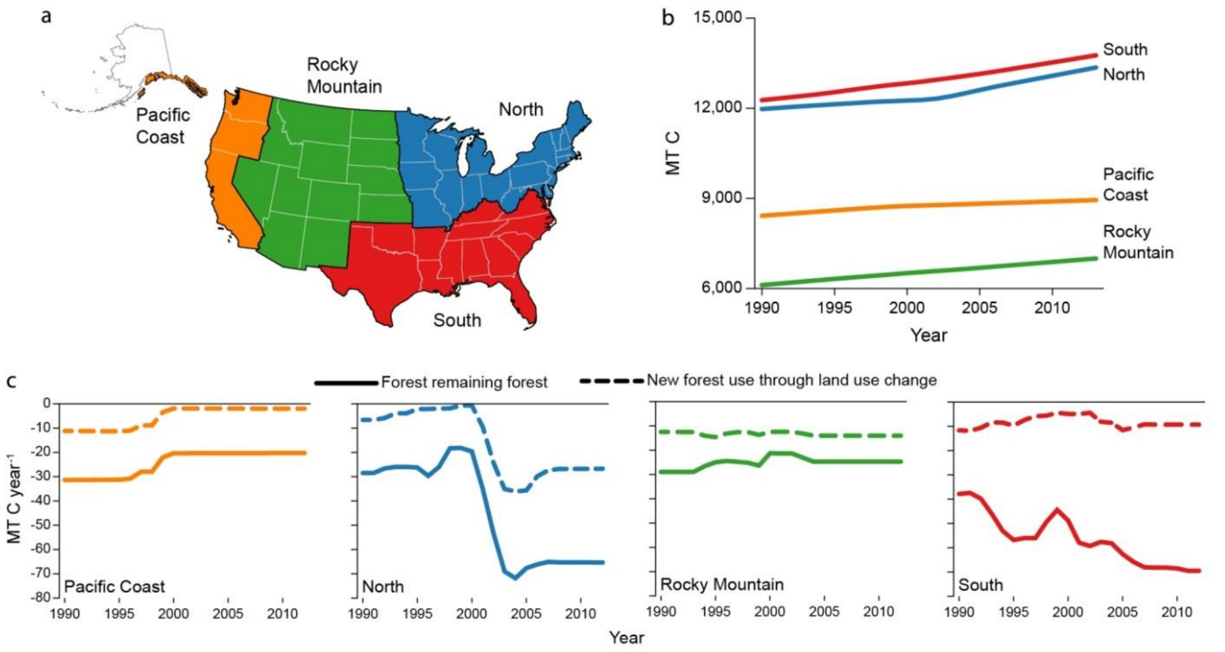
Source: Heath et al. 2003

Approximately 34 percent of the U.S. land area is estimated to be forested (Oswalt et al. 2014). The most-recent forest inventories from each of the conterminous 48 states (USDA Forest Service 2014a, 2014b, and see Annex Table A-246) include an estimated 264 million hectares of forest land that are considered managed and are included in this inventory. An additional 6 million hectares of southeast and south central Alaskan forest are inventoried and are included here. Some differences exist in forest land defined in Oswalt et al. (2014) and the forest land included in this report, which is based on the USDA Forest Service (2014b) forest inventory. Survey data are not yet available for Hawaii and interior Alaska, but estimates of these areas are included in Oswalt et al. (2014). Updated survey data for central and western forest land in both Oklahoma and Texas have only recently become available, and these forests contribute to overall C stocks reported below. While Hawaii and U.S. territories have relatively small areas of forest land and thus may not influence the overall C budget substantially, these regions will be added to the C budget as sufficient data become available. Agroforestry systems are also not currently accounted for in the inventory, since they are not explicitly inventoried by either the FIA program of the USDA Forest Service or the NRI of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 68 percent (211 million hectares) of U.S. forests in Alaska and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Ten percent of Alaskan forests and 80 percent of forests in the conterminous United States are classified as timberlands. Of the remaining non-timberland forests, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 69 million hectares are lower productivity forest lands (Oswalt et al. 2014). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest lands.

Estimates of forest land area declined by approximately 8 million hectares over the period from the early 1960s to the late 1980s. Since then, forest area has increased by about 14 million hectares (Oswalt et al. 2014). Current trends in the managed forest area represented here increased by an average annual rate of 0.1 percent (see Annex Table A-248). In addition to the increase in forest area, the major influences on the current net C flux from forest land are management activities and the ongoing impacts of previous land-use changes. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems. For example, intensified management of forests that leads to an increased rate of growth may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of C.[29] Though harvesting forests removes much of the aboveground C, on average the estimated volume of annual net growth nationwide is about double the volume of annual removals on timberlands (Oswalt et al. 2014). The reversion of cropland or grassland to forest land increases C storage in biomass, forest floor, and soils. Emerging research into forest ecosystem C stock change for forest remaining forest versus land-use change transfers to the forest land use suggest that forest ecosystem C accretion continues at steady rates in most regions of the United States (Figure 6-3) due to the aforementioned drivers. In concert with this trend, conversion of croplands and grasslands to forest lands continues to facilitate net increases in forest C stocks over time especially in northern and southern regions. The net effects of forest management and the effects of land-use change involving forest land are captured in the estimates of C stocks and fluxes presented in this chapter.

Figure 6-3: Forest Ecosystem Carbon (All Pools) Stocks and Stock Change (1990-2013)



Forest ecosystem C (all pools) stocks and stock change (1990–2013) analysis attributable to forest remaining forest and land-use change transfers to forests: (a) Resource planning act assessment regions, (b) forest ecosystem stocks by region, (c) annual stock change in forest ecosystem C by region decomposed into net transfers into the forest C pool through land-use change and the net C accumulation in forests remaining forest (including disturbance related mortality and growth) (for analytical techniques see Coulston et al. in review and Wear and Coulston 2014).

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2013. 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 C 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

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[29] The term “biomass density” refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is 50 percent C by weight.

harvests have also affected net C fluxes. Because most of the timber harvested from U.S. forests is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). The size of these long-term C storage pools has increased during the last century with the question arising as to how long the U.S. forests can remain a net C sink (Woodall et al. 2013).

Changes in C stocks in U.S. forests and harvested wood were estimated to account for net sequestration of 775.7 MMT CO_2 Eq. (211.5 MMT C) in 2013 (Table 6-8, Table 6-9, and Table 6-10). In addition to the net accumulation of C in harvested wood pools, sequestration is a reflection of net forest growth and increasing forest area over this period. Overall, estimates of average C in forest ecosystem biomass (aboveground and belowground) increased from 55 to 66 T C/ha between 1990 and 2014 (see Annex 3.13 for estimated average C densities by specific regions and forest types). Continuous, regular annual surveys are not available over the period for each state; therefore, estimates for non-survey years were derived by interpolation between known data points. Survey years vary from state to state, and national estimates are a composite of individual state surveys. Therefore, changes in sequestration over the interval 1990 to 2013 are the result of the sequences of new inventories for each state. Carbon in forest ecosystem biomass had the greatest effect on total change through increases in C density and total forest land. Management practices that increase C stocks on forest land, as well as afforestation and reforestation efforts, influence the trends of increased C densities in forests and increased forest land in the United States.

Estimated annual net additions to HWP C stock increased slightly between 2012 and 2013. Estimated net additions to solid-wood products in use increased a little with further recovery of the housing market, but additions to paper products in use declined. Estimated net additions to products in use for 2013 is about 20 percent of the level of net additions to products in use in 2007—prior to the recession. Estimated additions to landfills have been relatively stable over time.

Table 6-8: Estimated Net Annual Changes in C Stocks (MMT CO_2/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	2005	2009	2010	2011	2012	2013
Forest	**(507.7)**	**(704.4)**	**(710.6)**	**(704.9)**	**(704.9)**	**(704.9)**	**(704.9)**
Aboveground	(324.6)	(402.8)	(433.8)	(433.7)	(433.7)	(433.7)	(433.7)
Belowground	(63.2)	(79.3)	(87.3)	(87.4)	(87.4)	(87.4)	(87.4)
Dead Wood	(45.9)	(66.8)	(94.2)	(95.0)	(95.0)	(95.0)	(95.0)
Litter	(26.8)	(11.8)	(11.2)	(10.9)	(10.9)	(10.9)	(10.9)
Soil Organic C	(47.2)	(143.8)	(84.1)	(77.9)	(77.9)	(77.9)	(77.9)
Harvested Wood	**(131.8)**	**(102.7)**	**(54.3)**	**(60.5)**	**(68.9)**	**(68.2)**	**(70.8)**
Products in Use	(64.8)	(42.9)	6.6	0.4	(7.3)	(6.2)	(8.4)
SWDS	(67.0)	(59.8)	(60.9)	(60.9)	(61.6)	(62.0)	(62.3)
Total Net Flux	**(639.4)**	**(807.1)**	**(764.9)**	**(765.4)**	**(773.8)**	**(773.1)**	**(775.7)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a portion of managed forests in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Forest area estimates are based on interpolation and extrapolation of Inventory data as described in the text and in Annex 3.13. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 6-9: Estimated Net Annual Changes in C Stocks (MMT C/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	2005	2009	2010	2011	2012	2013
Forest	**(138.5)**	**(192.1)**	**(193.8)**	**(192.2)**	**(192.2)**	**(192.2)**	**(192.2)**
Aboveground Biomass	(88.5)	(109.9)	(118.3)	(118.3)	(118.3)	(118.3)	(118.3)
Belowground Biomass	(17.2)	(21.6)	(23.8)	(23.8)	(23.8)	(23.8)	(23.8)
Dead Wood	(12.5)	(18.2)	(25.7)	(25.9)	(25.9)	(25.9)	(25.9)
Litter	(7.3)	(3.2)	(3.1)	(3.0)	(3.0)	(3.0)	(3.0)
Soil Organic C	(12.9)	(39.2)	(22.9)	(21.2)	(21.2)	(21.2)	(21.2)
Harvested Wood	**(35.9)**	**(28.0)**	**(14.8)**	**(16.5)**	**(18.8)**	**(18.6)**	**(19.3)**
Products in Use	(17.7)	(11.7)	1.8	0.1	(2.0)	(1.7)	(2.3)
SWDS	(18.3)	(16.3)	(16.6)	(16.6)	(16.8)	(16.9)	(17.0)

Total Net Flux	**(174.4)**	**(220.1)**	**(208.6)**	**(208.7)**	**(211.0)**	**(210.8)**	**(211.5)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a portion of managed lands in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C 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 and harvested wood C storage pools are presented in Table 6-10. Together, the estimated aboveground live and forest soil pools account for a large proportion of total forest C stocks. The estimated C stocks summed for non-soil pools increased over time. Therefore, the estimated C sequestration was greater than C emissions from forests, as discussed above. Although not using the same pool delineations as this inventory submission, recent research into imputing FIA plot data across the coterminous United States allows spatial interpretation of forest C pools (Wilson et al. 2013). The imputed C density of individual forest ecosystem pools is highly variable across the diverse ecosystems of the United States (see Figure 6-5) highlighting the technical hurdles in refining C accounting across the matrix of changing land uses and ecosystem dynamics (e.g., temperate versus subtropical forests).

Table 6-10: Estimated Forest area (1,000 ha) and C Stocks (MMT C) in Forest and Harvested Wood Pools

	1990	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Forest Area (1000 ha)	***265,938***	***268,334***	***269,396***	***269,536***	***269,661***	***269,786***	***269,911***	***270,035***
Carbon Pools (MMT C)								
Forest	**36,309**	**38,429**	**39,214**	**39,408**	**39,600**	**39,792**	**39,985**	**40,177**
Aboveground Biomass	12,266	13,727	14,188	14,306	14,425	14,543	14,661	14,780
Belowground Biomass	2,430	2,717	2,809	2,833	2,857	2,881	2,904	2,928
Dead Wood	2,138	2,384	2,470	2,496	2,522	2,548	2,574	2,600
Litter	2,749	2,803	2,816	2,819	2,822	2,825	2,828	2,831
Soil Organic C	16,726	16,798	16,931	16,954	16,975	16,996	17,017	17,038
Harvested Wood	**1,859**	**2,325**	**2,431**	**2,446**	**2,462**	**2,481**	**2,500**	**2,520**
Products in Use	1,231	1,435	1,473	1,472	1,471	1,473	1,475	1,478
SWDS	628	890	958	974	991	1,008	1,025	1,042
Total C Stock	**38,168**	**40,754**	**41,645**	**41,854**	**42,062**	**42,273**	**42,485**	**42,697**

Note: Forest area and carbon stock estimates include all forest land in the conterminous 48 states plus managed forests in coastal Alaska (Figure 6-6), which is the current area encompassed by FIA survey data. A recent methodological change implemented to address missing forest area data in coastal Alaska resulted in discrepancies between the coastal Alaska managed forest area of 1990 through 2014, as contributes to this table, and the areas presented in Section 6.1 "Representation of the United S Land Base". Coastal Alaska managed forest lands contributing to this table changed linearly from 5.77 million hectares in 1990 to 5.86 million hectares in 2014. The estimates used for Section 6 changed linearly from 5.48 million hectares in 1990 to 5.95 million hectares in 2014. This represents a change of 5.3 and -1.5 percent for 1990 and 2014 in coastal Alaska, respectively. This discrepancy will be corrected in the 2016 submission. Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Forest area estimates are based on interpolation and extrapolation of Inventory data as described in Smith et al. (2010) and in Annex 3.13. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Inventories 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 2013 requires estimates of C stocks for 2013 and 2014.

Figure 6-4: Estimates of Net Annual Changes in C Stocks for Major C Pools

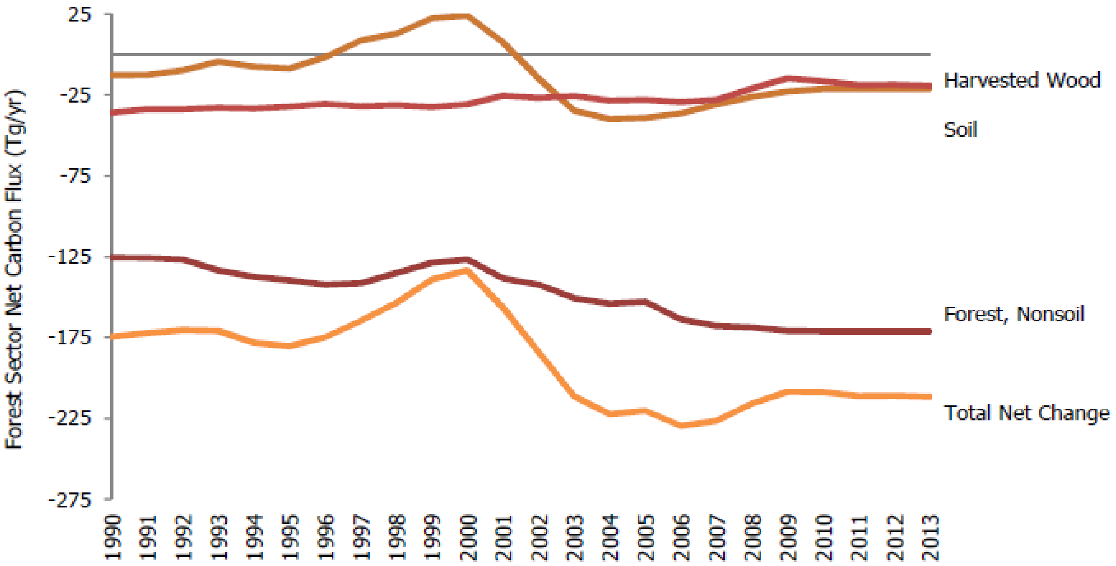


Figure 6-5: Forest Ecosystem C Density Imputed from Forest Inventory Plots, Conterminous United States, 2001–2009

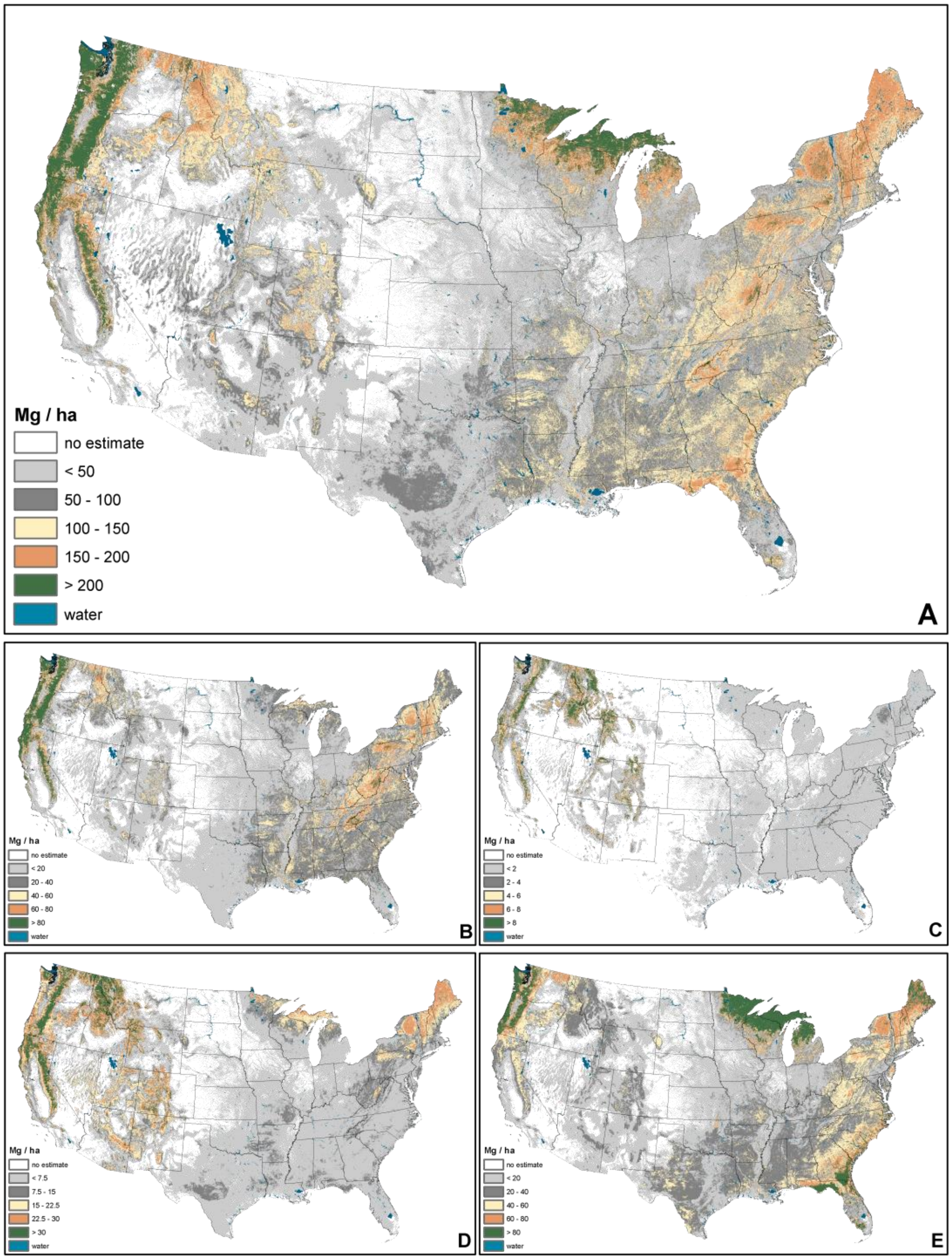


Figure 6-5 shows: (A) Total forest ecosystem C, (B) aboveground live trees, (C) standing dead trees, (D) litter, and (E) soil organic C (Wilson et al. 2013).

Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly accounts for emissions due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A forest fire disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forest land already account for CO_2 emissions from forest fires occurring in the lower 48 states as well as in the proportion of Alaska's managed forest land captured in this Inventory. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these estimates are highlighted here, using the full extent of available data. Non-CO_2 greenhouse gas emissions from forest fires are also quantified in a separate section below.

The IPCC (2003) methodology and IPCC (2006) default combustion factor for wildfire were employed to estimate CO_2 emissions from forest fires. See the explanation in Annex 3.13 for more details on the methodology used to estimate CO_2 emissions from forest fires. Carbon dioxide emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2013 were estimated to be 77.9 MMT CO_2/yr. This amount is masked in the estimate of net annual forest C stock change for 2013 because this net estimate accounts for the amount sequestered minus any emissions.

Table 6-11: Estimates of CO_2 (MMT/yr) Emissions from Forest Fires for the Lower 48 States and Alaska

Year	CO_2 emitted from Wildfires in Lower 48 States (MMT/yr)	CO_2 emitted from Prescribed Fires in Lower 48 States (MMT/yr)	CO_2 emitted from Wildfires in Alaska (MMT/yr)	Total CO_2 emitted (MMT/yr)
1990	28.8	4.9	+	33.7
2005	95.8	14.8	+	110.7
2009	63.5	14.5	+	77.9
2010	49.5	13.9	+	63.4
2011	182.7	12.2	+	194.9
2012	197.7	11.5	+	209.1
2013	66.2	11.7	+	77.9

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: These emissions have already been accounted for in the estimates of net annual changes in C stocks, which account for the amount sequestered minus any emissions.

Methodology and Data Sources

The methodology described herein is consistent with IPCC (2006). Forest ecosystem C stocks and net annual C stock change were determined according to stock-difference methods, which involved applying C estimation factors to forest inventory data and interpolating between successive inventory-based estimates of C stocks. Harvested wood C 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 C in forest ecosystems or harvested wood products is provided here. See Annex 3.13 for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

Forest ecosystem stock and flux estimates are based on the stock-difference method and calculations for all estimates are in units of C. Separate estimates were made for the five IPCC C storage pools described above. All estimates were based on data collected from the extensive array of permanent forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2013b, 2013c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. A combination of tiers as outlined by IPCC (2006) were used. The Tier 3 biomass C estimates were calculated from forest inventory tree-level data. The Tier 2 dead organic and soil C estimates were obtained from empirical or theoretical models using the inventory data. All C conversion factors are specific to regions or individual states within the United States, which were further classified according to characteristic forest types within each region.

The first step in developing forest ecosystem estimates is to identify useful inventory data and resolve any inconsistencies among datasets. Forest inventory data were obtained from the FIA program (Frayer and Furnival 1999, USDA Forest Service 2014b). 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 more recent annual inventories reported for states are represented as “moving window” averages, which means that a portion—but not all—of the previous year’s inventory is updated each year (USDA Forest Service 2014d). Forest C calculations are organized according to these state surveys, and the frequency of surveys varies by state. All available datasets are identified for each state starting with pre-1990 data, and all unique surveys are identified for stock and change calculations. Since C stock change is based on differences between successive surveys within each state, accurate estimates of net C flux thus depend on consistent representation of forest land between these successive inventories. In order to achieve this consistency from 1990 to the present, states are sometimes subdivided into sub-state areas where the sum of sub-state inventories produces the best whole-state representation of C change as discussed in Smith et al. (2010).

The principal FIA datasets employed are freely available for download at USDA Forest Service (2014b) as the Forest Inventory and Analysis Database (FIADB) Version 6.0 (USDA Forest Service 2014c). However, to achieve consistent representation (spatial and temporal), three other general sources of past FIA data were included as necessary. First, older FIA plot- and tree-level data—not in the current FIADB format—are used if available. Second, Resources Planning Act Assessment (RPA) databases, which are periodic, plot-level only, summaries of state inventories, are used to provide the data at or before 1990. Finally, the Integrated Database (IDB), which is a compilation of periodic forest inventory data from the 1990s for California, Oregon, and Washington is used (Waddell and Hiserote 2005). These IDB data were identified by Heath et al. (2011) as the most appropriate non-FIADB sources for these states and are included in this Inventory. See USDA Forest Service (2014a) for information on current and older data as well as additional FIA Program features. A detailed list of the specific forest inventory data used in this Inventory is included in Annex 3.13.

Modifications to the use of some of the FIADB surveys or subsequent C conversions were initiated for this report. First, the most-recent FIA population summary (known as an evaluation within the FIADB) was incorporated into all states’ stock-change calculations which stands in contrast to the approach in previous years where most of the newest evaluations were already in use, but if the majority of the underlying plots in the most recent population were also a part of the previous population (i.e., over 50 percent redundant plots) then the recent population was considered insufficiently unique and not used for calculation. Second, modifications were conducted in coastal Alaska for developing net annual change estimates (see Annex 3.13) and separating managed versus unmanaged forest lands in order to exclude C stock and stock-change on unmanaged forest land (IPCC 2006, Ogle et al. in preparation). This reduced the plots contributing to the Alaska forest C estimates by about 5 percent. A third modification to the use of the FIADB-defined forest land, introduced this year, was applied to identify plots on woodland forest types that do not meet the height requirement within the definition of forest land (Oswalt et al. 2014, Coulston et al. in preparation). These plots were identified as “other wooded lands” (i.e., not “forest” within the FIA forest inventory) and provided as C density information to the grasslands land-use category as the plots were not a complete inventory of the grassland land-use category in the United States. Finally, a new model estimating plot level C density of litter was developed and incorporated into the C budget (Domke et al. in preparation).

Forest C stocks were estimated from inventory data by a collection of conversion factors and models (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004, Smith et al. 2006, Woodall et al. 2011a, Domke et al. 2011, Domke et al. 2012, Domke et al. in preparation), which have been formalized in an FIADB-to-C calculator (Smith et al. 2010). The conversion factors and model coefficients were categorized by region and forest type, and forest C stock estimates were calculated from application of these factors at the scale of FIA inventory plots. The results were estimates of C density (T C per hectare) for six forest ecosystem pools: Live trees, standing dead trees, understory vegetation, downed dead wood, forest floor, and soil organic matter. The six C pools used in the FIADB-to-C calculator were aggregated to the five C pools defined by IPCC (2006): Aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter. The live-tree and understory C were pooled as biomass, and standing dead trees and downed dead wood were pooled as dead wood, in accordance with IPCC (2006).

Once plot-level C stocks were calculated as C densities on *Forest Land Remaining Forest Land* for the five IPCC (2006) reporting pools, the stocks were expanded to population estimates according to methods appropriate to the respective inventory data (for example, see Bechtold and Patterson (2005)). These expanded C stock estimates were summed to state or sub-state total C stocks. Annualized estimates of C stocks were developed by using available FIA inventory data and interpolating or extrapolating to assign a C stock to each year in the 1990 through 2014 time series. Flux, or net annual stock change, was estimated by calculating the difference in stocks between two successive years and applying the appropriate sign convention; net increases in ecosystem C were identified as negative flux. By convention, inventories were assigned to represent stocks as of January 1 of the inventory year; an estimate of flux for 1996 required estimates of C stocks for 1996 and 1997, for example. Additional discussion of the use of FIA inventory data and the C conversion process is in Annex 3.13.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above- and below-ground biomass components. If inventory plots included data on individual trees, tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method. Some of the older forest inventory data in use for these estimates did not provide measurements of individual trees. Examples of these data include plots with incomplete or missing tree data or the RPA plot-level summaries. The C estimates for these plots were based on average densities (T C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to less than 5 percent of the forest land inventory-plot-to-C conversions within the 214 state-level surveys utilized here.

Understory vegetation is a minor component of biomass, which is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. In the current Inventory, it was assumed that 10 percent of total understory C mass is belowground. Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory frequently represented over 1 percent of C in biomass, but its contribution rarely exceeded 2 percent of the total.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models. The standing dead tree C pools include aboveground and belowground (coarse root) mass and include trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011, Harmon et al. 2011). Similar to the situation with live tree data, some of the older forest inventory data did not provide sufficient data on standing dead trees to make accurate population-level estimates. The C estimates for these plots were based on average densities (T C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applied to less than 20 percent of the forest land inventory-plot-to-C conversions within the 214 state-level surveys utilized here. 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 C 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 C is the pool of organic C (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. Estimates are based on Domke et al. (in preparation).

Carbon in Forest Soil

Soil organic C includes all organic material in soil to a depth of 1 meter but excludes the coarse roots of the biomass or dead wood pools. Estimates of SOC were based on the national STATSGO spatial database (USDA 1991), which includes region and soil type information. Soil organic C determination was based on the general approach described by Amichev and Galbraith (2004). Links to FIA inventory data were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil C map. This method produced mean SOC densities stratified by region and forest type group. It did not provide separate estimates for mineral or organic soils but instead weighted their contribution to the overall average based on the relative amount of each within forest land. Thus, forest SOC is a function of species and location, and net change also depends on these two factors as total forest area changes. In this respect, SOC provides a country-specific reference stock for 1990 through the present, but it does not reflect the effects of past land use.

Harvested Wood Carbon

Estimates of the HWP contribution to forest C 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 HWP C. IPCC (2006) provides methods that allow for reporting of HWP Contribution using one of several different accounting approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.13 for more details about each approach). The United States used the production accounting approach to report HWP Contribution. Under the production approach, C in exported wood was estimated as if it remains in the United States, and C in imported wood was not included in inventory 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 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 solid waste disposal sites (SWDS). Emissions from HWP associated with wood biomass energy are not included in this accounting—a net of zero sequestration and emissions as they are a part of energy accounting (see Chapter 3).

Solidwood products added to pools 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 that additions of softwood lumber to housing began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and 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, forthcoming). Estimates for disposal of products reflected 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 C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C 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 C 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) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C 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 accounting approach. A key assumption for estimating these variables 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 and Time Series Consistency

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems as well as C in harvested wood products through Monte Carlo Stochastic Simulation of the Methods described above and probabilistic sampling of C conversion factors and inventory data. See Annex 3.13 for additional information. The 2013 net annual change for forest C stocks was estimated to be between -972.9 and -575.9 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of -900.7 to -505.9 MMT CO_2 Eq. for forest ecosystems and -89.9 to -54.0 MMT CO_2 Eq. for HWP.

Table 6-12: Approach 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Forest Land Remaining Forest Land: Changes in Forest C Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Forest Ecosystem	CO_2	(704.9)	(900.7)	(505.9)	−27.8	28.2
Harvested Wood Products	CO_2	(70.8)	(89.9)	(54.0)	−27.0	23.7
Total Forest	**CO_2**	**(775.7)**	**(972.9)**	**(575.9)**	**−25.4**	**25.8**

Note: Parentheses indicate negative values or net sequestration.

[a] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States, 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 C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2014d).

Many key calculations for estimating current forest C stocks based on FIA data were developed to fill data gaps in assessing forest C and have been in use for many years to produce national assessments of forest C stocks and stock changes (see additional discussion and citations in the Methodology section above and in Annex 3.13). General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the derived C datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Smith et al. (2009) or selected population estimates generated from FIADB 6.0, which are available at an FIA internet site (USDA Forest Service 2014b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used. Finally, C stock estimates were compared with previous Inventory report estimates to ensure that any differences could be explained by either new data or revised calculation methods (see the "Recalculations" discussion, below).

Estimates of the HWP variables and the HWP contribution under the production accounting approach use data from U.S. Census and USDA Forest Service surveys of production and trade. Factors to convert wood and paper to units of C are based on estimates by industry and Forest Service published sources. The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solid wood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C 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 each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in C in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in C 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

Forest ecosystem stock and stock-change estimates differ from the previous Inventory (EPA 2014) principally due to some changes in data and methods (see discussion above in Methodology and in Annex 3.13). The net effect of the modifications was to slightly reduce net C uptake (i.e., lower sequestration) and C stocks from 1990 to the present. The influence of the individual modifications on stock and stock-change varied considerably; these were evaluated to identify the relative sensitivity of totals to each. That is, the analysis identified where the estimates (as in Tables Table 6-8 through Table 6-10) were most affected by the revised methods incorporated with this report. First, the collective effects of selecting FIA population estimates and updates to the annual forest inventories for many states had the effect of decreasing sequestration in early years while increasing after 2005 and had the greatest effect on determining overall stock-change estimates for 2006 and 2007, but otherwise this modification was a minor influence. Second, the application of a new managed land definition as part of the land representation analysis (see Section 6.1) and the subsequent decrease in managed forest lands along coastal Alaska affected that individual state's estimates but had minimal effect on C stock estimates for the United States as a whole. Third, the reallocation of selected woodlands from forest land (i.e., these "other wooded lands" were then classified as grasslands) had the greatest effect on annualized estimates of forest area throughout the time series. In addition, the removal of these lands from forest had the greatest effect on total forest stock-change through the early 1990s, yet the reclassification did tend to decrease sequestration throughout the entire time series. Finally, the revised litter C estimates generally had a lower influence on stock-change relative to the woodland modification. However, the revised litter estimates increased sequestration through the 1990s but decreased sequestration over more recent years. In addition, the change in estimated litter C had the greatest effect on forest ecosystem stocks throughout the time period.

The estimate of net annual change in HWP C stock and total C stock in HWP were revised upward by small amounts. The increase in total net annual additions compared to estimates published in 2013 was 2 to 3 percent for 2010 through 2012. This increase was mostly due to changes in the amount of pulpwood used for paper and composite panel products back to 2003. All the adjustments were made as a result of corrections in the database of forest products statistics used to prepare the estimates (Howard forthcoming).

Planned Improvements

Reliable estimates of forest C across the diverse ecosystems/industries 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: Pool estimation techniques, land use and land-use change, and field inventories.

In an effort to reduce the uncertainty associated with the estimation of individual forest C pools, the empirical data and associated models for each pool are being evaluated for potential improvement (Woodall 2012). In the 1990 through 2010 Inventory report, the approach to tree volume/biomass estimation was evaluated and refined (Domke et al. 2012). In the 1990 through 2011 Inventory report, the standing dead tree C model was replaced with a nationwide inventory and associated empirical estimation techniques (Woodall et al. 2012, Domke et al. 2011, Harmon et al. 2011). In the 1990 through 2012 Inventory report the downed dead tree C model was refined by incorporation of a national field inventory of downed dead wood (Woodall et al. 2013, Domke et al. 2013). In the current Inventory report, the litter C density model was refined with a nearly nationwide field inventory (Domke et al. in preparation). The exact timing of future pool estimation refinements is dependent on the completion of current research efforts. Research is underway to use a national inventory of SOC (Woodall et al. 2011b) to refine the estimation of this pool. It is expected that improvements to SOC estimation will be incorporated into the 1990 through 2015 Inventory report. Components of other pools, such as C in belowground biomass (Russell et al. in preparation) and understory vegetation (Russell et al. in press), are being explored but may require additional investment in field inventories before improvements can be realized with Inventory submissions.

Despite the continuing accumulation of new data within the consistent nationwide field inventory of forests that is measured annually, additional research advances are needed to attain a complete, consistent, and accurate time series of annual land-use and land-use change matrices from 1990 to the present report year. Lines of research have been initiated to more fully examine land-use change within the FIA inventory system (see Figure 6-3; Coulston et al. in review, Wear and Coulston 2014) and bring together disparate sets of land-use information (e.g., forest versus croplands) that rely on remotely sensed imagery from the 1980s to the present (NASA CMS 2013). These lines of research are expected to require at least a few years for completion with subsequent time needed for application to future Inventory submissions.

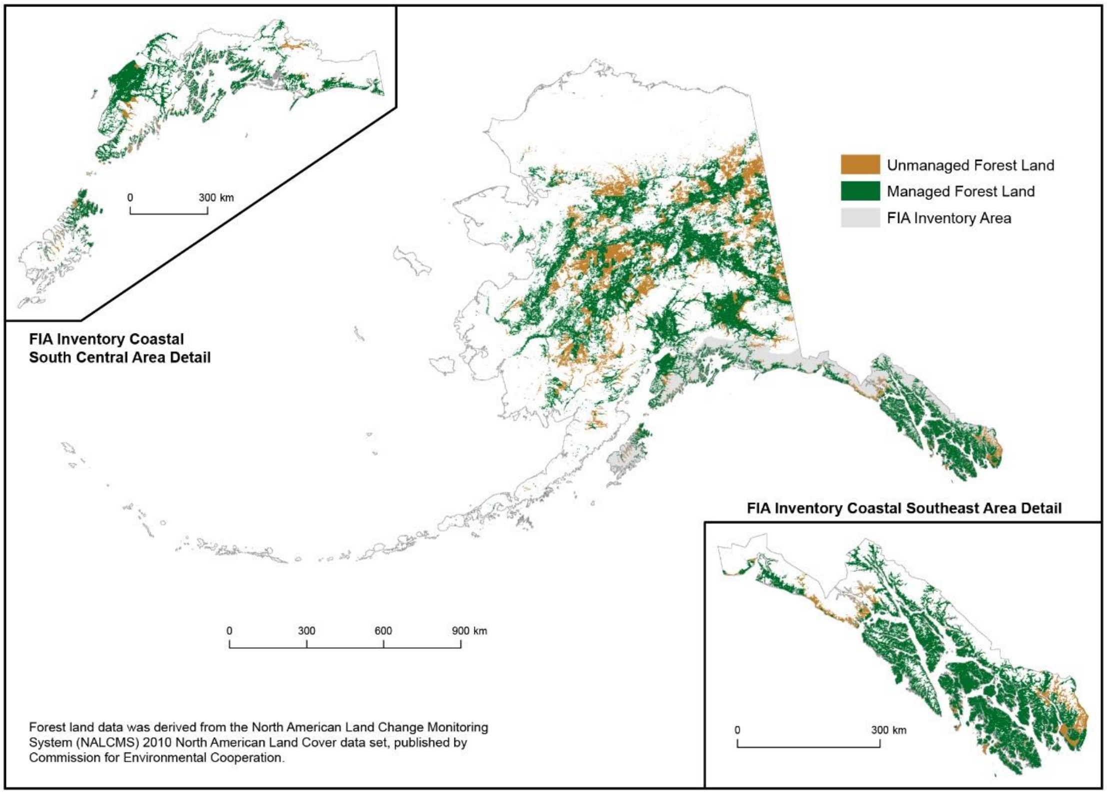
The foundation of forest C accounting is the annual forest inventory system. The ongoing annual surveys by the FIA Program are expected to improve the accuracy and precision of forest C estimates as new state surveys become available (USDA Forest Service 2013b), particularly in western states. Hawaii and U.S. territories will be included when appropriate forest C data are available (as of July 21, 2014, Hawaii is not yet reporting any data from the annualized sampling design). In addition, the more intensive sampling of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve resolution of C pools (i.e., greater sample intensity; Westfall et al. 2013) this information becomes available (Woodall et al. 2011b). Increased sample intensity of some C pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The USDA Forest Service FIA Program’s forest and wooded land inventories extend beyond the forest land-use (e.g., woodlands and urban areas), and Inventory-relevant information for these lands will likely become increasingly available in coming years.

Towards an Accounting of Managed Forest Carbon in Interior Alaska

Given the remote nature and vast expanse of forest across the state of Alaska, consistent inventories of all Alaskan forest land have never been conducted. Figure 6-6 compares the vast expanse of Alaska to countries in Europe, which in large part explains the lack of a consistent forest inventory and provides an indication of the extent of any effort to include an area of this magnitude using the existing forest inventories for the United States. Starting in the 1990s, a forest inventory of south central and southeastern coastal (SCSE) Alaska was initiated following the same approach applied in the conterminous United States (see Figure 6-7).

Figure 6-6: The Size of Alaska Compared to European Countries

Figure 6-7: Delineations between Forest, Non-forest, Managed Land, and Inventoried Areas of Alaska



Forest land data was derived from the North American Land Change Monitoring System (NALCMS) 2010 North American Land Cover data set, published by Commission for Environmental Cooperation.

Establishment and data collection on these plots began in 1995 with the current inventory nearing completion of a full re-measurement (i.e., one cycle of periodic inventory represented by the 2003 data and 90 percent of an annual inventory cycle represented by the 2012 data). Forest C estimates for SCSE Alaska were first included in the Inventory in 2008. The managed forest land in SCSE Alaska has been the only contribution to the Inventory since 2008 owing to the lack of a consistent inventory across the much larger interior portion of Alaska that generally includes less productive forest lands.

Recognizing the need to inventory interior Alaskan forests for the Inventory and resource management, research is being conducted towards these ends:

- A spatial model delineating managed and unmanaged lands for Alaska was developed in part to better align greenhouse gas reporting with managed lands for Alaskan forests (Ogle et al. in preparation). In contrast to Alaska, all forest lands in the conterminous 48 states are considered managed for purposes of greenhouse gas reporting. The spatial model of managed lands for Alaska is applied to both the preliminary assessment of interior Alaskan forest C provided here and the reported C of SCSE Alaska in order to align with the practice of reporting of forest C on managed lands per IPCC (2006) *Good Practice Guidelines*.
- Research continues to better appraise the forest C stocks and their associated dynamics across the Alaskan landscape that rely on remotely sensed imagery and limited in situ measurements. Based on this emerging work the amount of managed forest land and ranges of C stocks will be estimated. This current work (McGuire et al. in preparation, Genet et al. in preparation, Saatchi et al. in preparation) has identified 46–49 million hectares of managed forestland in interior Alaska. This represents 68 percent of total interior forest land. Live biomass (e.g., vegetation) C stocks are estimated to range between 1,600 and 2,100 MMT C and non-live biomass (e.g., soils, deadwood, litter) is estimated to range between 6,100 and 13,000 MMT C), all with concomitant high levels of uncertainty.

- A joint USDA Forest Service-National Aeronautics and Space Administration research effort was conducted in interior Alaska during the summer of 2014 where high-resolution airborne scanning laser, hyperspectral, and thermal imagery were collected in a sampling mode over the entire Tanana valley (135,000 km^2). These remotely-sensed data will be combined with a limited number of in situ plot measurements (100 FIA plots collected within the Tanana Valley State Forest and Tetlin National Wildlife Refuge) to explore potential application across interior Alaska (NASA CMS 2014). Results from this research study are expected within a few years.

As preliminary research results suggest that the managed forest C stock may be upwards of 15,000 MMT C or 37 percent of the United States' managed forest C stock in the current Inventory, care must be given to vet all emerging research especially in regards to stock change. It is hoped that the managed forest land base in interior Alaska might be included in future Inventories if: (a) adequate funding resources become available, and (b) research into combining remotely sensed technologies with in situ measurements (especially of non-vegetation pools) is a success.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using the default IPCC (2003) methodology incorporating default IPCC (2006) emissions factors and combustion factor for wildfires. Emissions from this source in 2013 were estimated to be 5.8 MMT CO_2 Eq. of CH_4 and 3.8 MMT CO_2 Eq. of N_2O, as shown in Table 6-13 and Table 6-14. The estimates of non-CO_2 emissions from forest fires account for wildfires in the lower 48 states and Alaska as well as prescribed fires in the lower 48 states.

Table 6-13: Estimated Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.) for U.S. Forests

Gas	1990	2005	2009	2010	2011	2012	2013
CH_4	2.5	8.3	5.8	4.7	14.6	15.7	5.8
N_2O	1.7	5.5	3.8	3.1	9.6	10.3	3.8
Total	**4.2**	**13.8**	**9.7**	**7.9**	**24.2**	**26.0**	**9.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2006).

Table 6-14: Estimated Non-CO_2 Emissions from Forest Fires (kt) for U.S. Forests

Gas	1990	2005	2009	2010	2011	2012	2013
CH_4	101	332	233	190	584	626	233
N_2O	6	18	13	11	32	35	13

Note: Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2006).

Methodology

The IPCC (2003) Tier 2 default methodology was used to calculate C and CO_2 emissions from forest fires. However, more up-to-date default emission factors from IPCC (2006) were converted into gas-specific emission ratios and incorporated into the methodology to calculate non-CO_2 emissions from C emissions. Estimates of CH_4 and N_2O emissions were calculated by multiplying the total estimated CO_2 emitted from forest burned by the gas-specific emissions ratios. CO_2 emissions were estimated by multiplying total C emitted (Table 6-15) by the C to CO_2 conversion factor of 44/12 and by 92.8 percent, which is the estimated proportion of C emitted as CO_2 (Smith 2008a). The equations used to calculate CH_4 and N_2O emissions were:

$$\mathrm{CH_4\ Emissions} = (\mathrm{C\ released}) \times 92.8\% \times (44/12) \times (\mathrm{CH_4\ to\ CO_2\ emission\ ratio})$$

$$\mathrm{N_2O\ Emissions} = (\mathrm{C\ released}) \times 92.8\% \times (44/12) \times (\mathrm{N_2O\ to\ CO_2\ emission\ ratio})$$

Where CH_4 to CO_2 emission ratio is 0.003 and N_2O to CO_2 emission ratio is 0.0002. See the explanation in Annex 3.13 for more details on the CH_4 and N_2O to CO_2 emission ratios.

Estimates for C emitted from forest fires are the same estimates used to generate estimates of CO_2 presented earlier in Box 6-3. Estimates for C emitted include emissions from wildfires in both Alaska and the lower 48 states as well as emissions from prescribed fires in the lower 48 states only (based on expert judgment that prescribed fires only occur in the lower 48 states) (Smith 2008a). The IPCC (2006) default combustion factor of 0.45 for "all 'other' temperate forests" was applied in estimating C emitted from both wildfires and prescribed fires. See the explanation in Annex 3.13 for more details on the methodology used to estimate C emitted from forest fires.

Table 6-15: Estimated C Released from Forest Fires for U.S. Forests (MMT/yr)

Year	C Emitted (MMT/yr)
1990	9.9
2005	32.5
2009	22.9
2010	18.6
2011	57.3
2012	61.5
2013	22.9

Uncertainty and Time-Series Consistency

Non-CO_2 gases emitted from forest fires depend on several variables, including: forest area for Alaska and the lower 48 states; average C densities for wildfires in Alaska, wildfires in the lower 48 states, and prescribed fires in the lower 48 states; emission ratios; and combustion factor values (proportion of biomass consumed by fire). To quantify the uncertainties for emissions from forest fires, a Monte Carlo (Approach 2) uncertainty analysis was performed using information about the uncertainty surrounding each of these variables. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-16.

Table 6-16: Approach 2 Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires in *Forest Land Remaining Forest Land* (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Non-CO_2 Emissions from Forest Fires	CH_4	5.8	1.1	15.2	−80%	+161%
Non-CO_2 Emissions from Forest Fires	N_2O	3.8	1.1	9.2	−71%	+139%

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

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 forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The current Inventory estimates for 1990 through 2013 were developed according to the methodology used in the previous Inventory report. However, the FIADB updates discussed in *Changes in Forest Carbon Stocks* affected forest C stocks, C density of litter, and total forest area, including the forest area estimates for coastal Alaska, all of which are used to calculate emissions estimates from forest fires. As a result of the FIADB updates, total non-CO_2 emissions from forest fires decreased by an average of 14 percent relative to emission estimates in the previous Inventory report.

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWP of CH_4 has increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWP of N_2O has decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

The combined effect of the FIADB updates and AR4 GWP values resulted in an average 7 percent decrease in total non-CO_2 emissions from wildfires and prescribed fires over the 1990 to 2012 time series.

Planned Improvements

The default combustion factor of 0.45 from IPCC (2006) was applied in estimating C emitted from both wildfires and prescribed fires. Additional research into the availability of a combustion factor specific to prescribed fires is being conducted.

Another area of improvement is to evaluate other methods of obtaining data on forest area burned by replacing ratios of forest land to land under wildland protection with Monitoring Trends in Burn Severity (MTBS) burn area data. MTBS data is available from 1984 through a portion of 2013. MTBS burn area data could be used to develop the national area burned and resulting CO_2 and non-CO_2 emissions. Additional research is required to determine appropriate uncertainty inputs for national area burned data derived from MTBS data.

N_2O Fluxes from Forest Soils (IPCC Source Category 4A1)

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). Thus, 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 forestland area.

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 in a form other than N_2O (NH_3 and NO_x volatilization, NO_3 leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct N_2O emissions from forest soils in 2013 were 0.3 MMT CO_2 Eq. (1 kt), and the indirect emission were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2013 were 0.5 MMT CO_2 Eq. (2 kt) and have increased by 455 percent from 1990 to 2013. Increasing emissions over the time series is a result of greater area of N fertilized pine plantations in the southeastern United States and Douglas-fir timberland in western Washington and Oregon. Total forest soil N_2O emissions are summarized in Table 6-17.

Table 6-17: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (MMT CO_2 Eq. and kt N_2O)

	1990		2005		2009	2010	2011	2012	2013
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	+		1		1	1	1	1	1
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	+	+	+	+	+	+	+
Total							
MMT CO_2 Eq.	**0.1**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
kt N_2O	**+**	**2**	**2**	**2**	**2**	**2**	**2**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 kt.

Methodology

The IPCC Tier 1 approach was used to estimate N_2O from soils within *Forest Land Remaining Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted were 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 accounted for 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 were 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). Not accounting for fertilizer applied to non-pine plantations is justified because fertilization is routine for pine forests but rare for hardwoods (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer was 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 were not available for 2005-2013, so data from 2004 were used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir was accounted for, because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area were multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data were not available for 2005 through 2013, so data from 2004 were used for these years. The annual area estimates were 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 was multiplied by the IPCC (2006) default emission factor of 1 percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land were calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized was multiplied by the IPCC default factor of 1 percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff was 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 were summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

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 C 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 N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only synthetic N fertilizers are captured, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils is included in the *Agricultural Soil Management* and *Settlements Remaining Settlements* sections.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates were assigned a default level[30] of uncertainty at ±50 percent, and area receiving fertilizer was assigned a ±20 percent according to expert knowledge (Binkley 2004). The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2013 emissions estimates. IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

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[30] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent was used in the analysis.

Quantitative uncertainty of this source category was estimated using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-18. Direct N_2O fluxes from soils were estimated to be between 0.1 and 1.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2013 emission estimate of 0.3 MMT CO_2 Eq. Indirect N_2O emissions in 2013 were between 0.02 and 0.4 MMT CO_2 Eq., ranging from 86 percent below to 238 percent above the 2013 emission estimate of 0.11 MMT CO_2 Eq.

Table 6-18: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
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	1.1	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	0.0	0.4	-86%	+238%

Note: These estimates include direct and indirect N_2O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The spreadsheet tab containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges were checked and corrected. Linkage errors in the uncertainty calculation for 2013 were found and corrected. The reported emissions in the NIR were also adjusted accordingly.

Recalculations Discussion

Indirect emissions from forest land were previously reported in *Agricultural Soil Management*, but are now included in this source category. Including indirect emissions resulted in a 27 percent increase.

Planned Improvements

Additional data will be compiled to update estimates of forest areas receiving N fertilizer as new reports are made available. Another improvement is to further disaggregate emissions by state for southeastern pine plantations and northwestern Douglas-fir forests to estimate soil N_2O emission. This improvement is contingent on the availability of state-level N fertilization data for forest land.

6.3 Land Converted to Forest Land (IPCC Source Category 4A2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to forest each year, just as forest land is converted to other uses. While the magnitude of these changes is known (see Table 6-5), research is ongoing to track C across *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* areas. Until such time that reliable and comprehensive estimates of C across these land use and land-use change categories can be produced, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Forest Land* from fluxes on *Forest Land Remaining Forest Land* at this time.

6.4 Cropland Remaining Cropland (IPCC Source Category 4B1)

Mineral and Organic Soil Carbon Stock Changes

Carbon (C) in cropland ecosystems occurs in biomass, dead biomass, and soils. However, C storage in biomass and dead organic matter is relatively ephemeral, with the exception of C stored in perennial woody crop biomass, such as citrus groves and apple orchards. Within soils, C is found in organic and inorganic forms of C, but soil organic C (SOC) is the main source and sink for atmospheric CO_2 in most soils. IPCC (2006) recommends reporting changes in SOC stocks due to agricultural land-use and management activities on both mineral and organic soils.[31]

Well-drained mineral soils typically contain from 1 to 6 percent organic C by weight, whereas mineral soils with high water tables for substantial periods during the year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the SOC to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of C 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, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net flux of C to or from the soil C pool (Parton et al. 1987, Paustian et al. 1997a, Conant et al. 2001, Ogle et al. 2005). Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C 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 C 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. Due to the depth and richness of the organic layers, C 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 C 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 used as cropland for the previous 20 years according to the 2007 USDA National Resources Inventory (NRI) land-use survey (USDA-NRCS 2009).[32] The inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but does not include the 1 to 1.5 million hectares of *Cropland Remaining Cropland* (less than 1 percent of the total cropland area in the United States) on federal lands between 1990 and 2013. In addition, approximately 28,700 hectares of cropland in Alaska are not included in this Inventory. This leads to a discrepancy between the total amount of managed area in *Cropland Remaining Cropland* (see Section 6.1) and the cropland area included in the Inventory. Improvements are underway to include croplands in Alaska and federal lands as part of future C inventories.

CO_2 emissions and removals[33] due to changes in mineral soil C stocks are estimated using a Tier 3 approach for the majority of annual crops (Ogle et al. 2010). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (i.e., vegetables, tobacco, perennial/horticultural crops, and rice) (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) and for additional changes in mineral soil C

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[31] CO_2 emissions associated with liming are also estimated but are included in a separate section of the report.

[32] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications were based on less than 20 years from 1990 to 2001.

[33] Note that removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil C pools.

stocks that were not addressed with the Tier 3 approach (i.e., change in C stocks after 2007 due to Conservation Reserve Program enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method.

Land-use and land management of mineral soils was the largest contributor to total net C stock change, especially in the early part of the time series (see Table 6-19 and Table 6-20). (Note: Estimates after 2007 are based on NRI data from 2007 and therefore do not fully reflect changes occurring in the latter part of the time series). In 2013, mineral soils were estimated to remove 45.6 MMT CO_2 Eq. (12.4 MMT C). This rate of C storage in mineral soils represented about a 49 percent decrease in the rate since the initial reporting year of 1990. Emissions from organic soils were 22.1 MMT CO_2 Eq. (6.0 MMT C) in 2013, which is an 8 percent decrease compared to 1990. In total, United States agricultural soils in *Cropland Remaining Cropland* sequestered approximately 23.4 MMT CO_2 Eq. (6.4 MMT C) in 2013.

Table 6-19: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Mineral Soils	(89.2)	(50.4)	(49.6)	(48.0)	(47.9)	(47.1)	(45.6)
Organic Soils	24.0	22.4	22.1	22.1	22.1	22.1	22.1
Total Net Flux	**(65.2)**	**(28.0)**	**(27.5)**	**(25.9)**	**(25.8)**	**(25.0)**	**(23.4)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Note: Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series

Table 6-20: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT C)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Mineral Soils	(24.3)	(13.8)	(13.5)	(13.1)	(13.1)	(12.9)	(12.4)
Organic Soils	6.5	6.1	6.0	6.0	6.0	6.0	6.0
Total Net Flux	**(17.8)**	**(7.6)**	**(7.5)**	**(7.1)**	**(7.0)**	**(6.8)**	**(6.4)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Note: Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series

The major cause of the reduction in soil C accumulation over the time series (i.e., 2013 is 49 percent less than 1990) is the decline in annual cropland enrolled in the Conservation Reserve Program (CRP)[34] which was initiated in 1985 (Jones et al., in prep). For example, over 2 million hectares of land in the CRP were returned to agricultural production, during the last 5 years resulting in a loss of soil C. However, positive increases in C stocks continue on the nearly 11 million hectares of land currently enrolled in the CRP, as well as from intensification of crop production by limiting the use of bare-summer fallow in semi-arid regions, increased hay production, and adoption of conservation tillage (i.e., reduced- and no-till practices).

The spatial variability in the 2013 annual CO_2 flux is displayed in Figure 6-8 and Figure 6-9 for C stock changes in mineral and organic soils, respectively. The highest rates of net C accumulation in mineral soils occurred in the Midwest, which is the region with the largest amounts of conservation tillage, with the next highest rates of accumulation in the South-central and Northwest regions of the United States. The regions with the highest rates of emissions from organic soils occur in the Southeastern Coastal Region (particularly Florida), upper Midwest and

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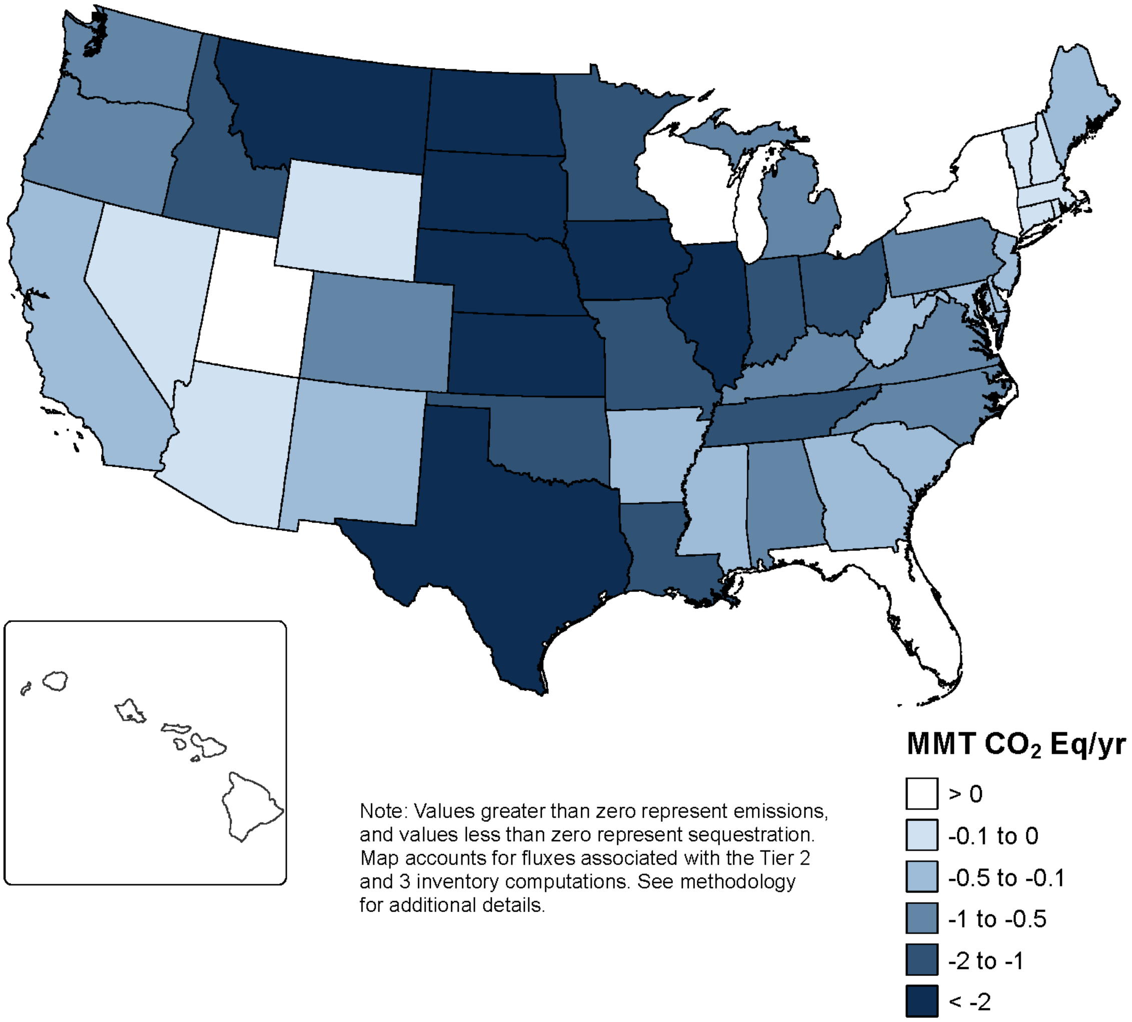
[34] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10-15 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.

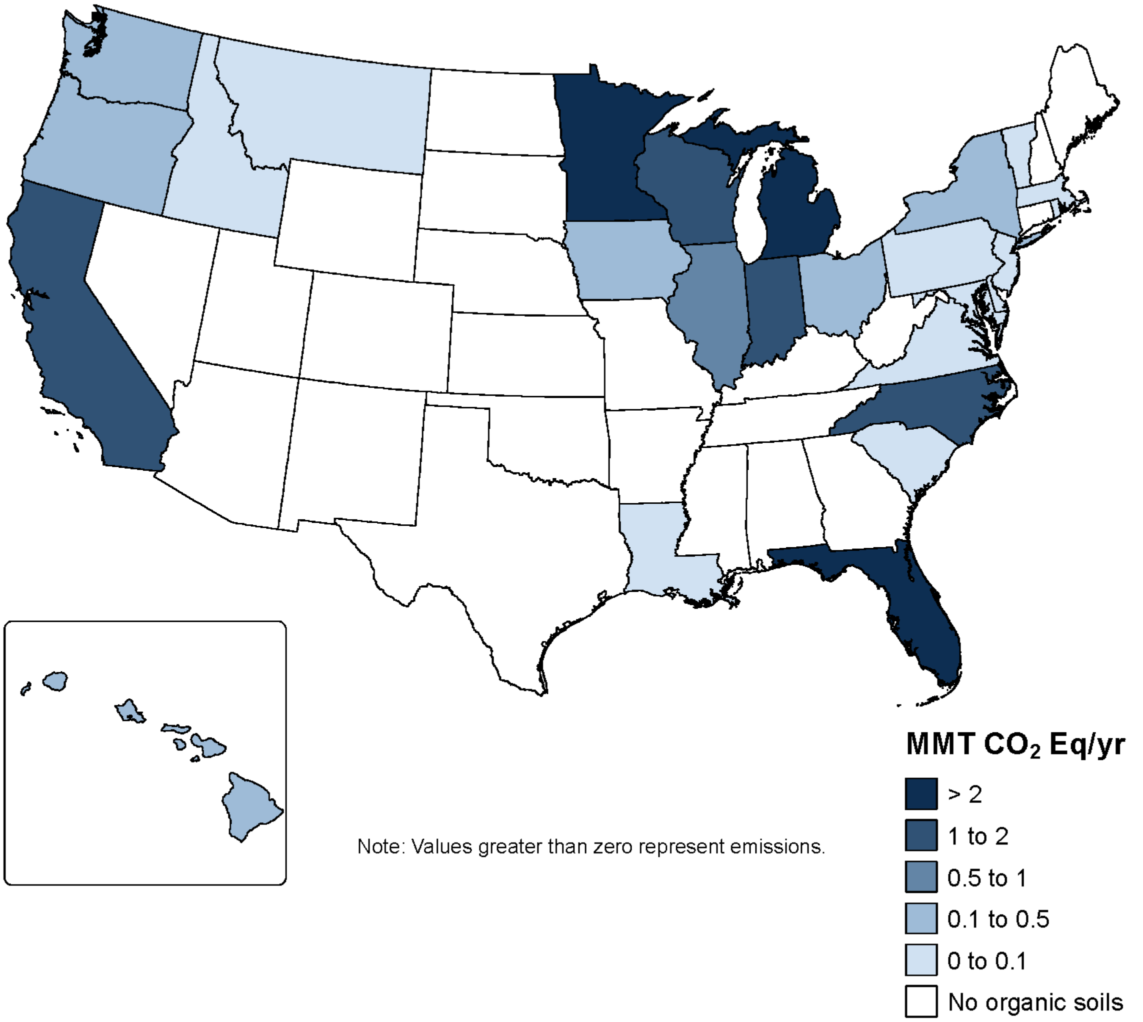
Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California), which coincides with largest concentrations of organic soils in the United States that are used for agricultural production.

Figure 6-8: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2013, *Cropland Remaining Cropland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See methodology for additional details.

Figure 6-9: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2013, *Cropland Remaining Cropland*



Note: Values greater than zero represent emissions.

Methodology

The following section includes a description of the methodology used to estimate changes in soil C 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.

Soil C stock changes were 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 (USDA-NRCS 2009). The NRI is a statistically-based sample of all non-federal land, and includes approximately 529,558 points in agricultural land for the conterminous United States and Hawaii.[35] Each point is associated with an "expansion factor" that allows scaling of C stock changes from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected for 4 out of 5 years in the cycle (i.e., 1979-1982, 1984-1987, 1989-1992,

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[35] NRI points were classified as agricultural if under grassland or cropland management between 1990 and 2007.

and 1994-1997). In 1998, the NRI program began collecting annual data, and data are currently available through 2010 (USDA-NRCS, 2013) although this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory. NRI points were classified as *Cropland Remaining Cropland* in a given year between 1990 and 2007 if the land use had been cropland for 20 years.[36] Cropland includes all land used to produce food and fiber, or forage that is harvested and used as feed (e.g., hay and silage), in addition to cropland that has been enrolled in the CRP (i.e., considered reserve cropland).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) was applied to estimate C stock changes for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. The model-based approach uses the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil C stock changes and soil nitrous oxide emissions from agricultural soil management. Carbon and N 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 C and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils.

The remaining crops on mineral soils were estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, tobacco, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method was also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). Mineral SOC stocks were 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 C stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. An additional stock change calculation was estimated for mineral soils using Tier 2 emission factors to account for enrollment patterns in the CRP after 2007, which was not addressed by the Tier 3 method.

Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.12.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical[37] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of C, N and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DAYCENT model utilizes the soil C 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. Crop production is simulated with NASA-CASA production algorithm (Potter et al.1993, Potter et al. 2007) using the MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250 m. A prediction algorithm was developed to estimate EVI (Gurung et al. 2009) for gap-filling during years over the inventory time series when EVI data were not available (e.g., data from the MODIS sensor were only available after 2000 following the launch of the Aqua and Terra Satellites). The modeling approach uses daily weather data as an input, along with information about soil physical properties. 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., planting, harvesting, fertilization, manure amendments, tillage, irrigation, residue removal, grazing, and fire). The model simulates net primary productivity and C additions to soil, soil temperature, and water dynamics, in addition to turnover, stabilization, and mineralization of soil organic matter C and nutrients (N, P, K, S). 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 6-4 for additional information).

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[36] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification prior to 2002 was based on less than 20 years of recorded land-use history for the time series.

[37] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment

Box 6-4: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil C stock changes on the majority of agricultural land on mineral soils. This approach results in a more complete accounting of soil C 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 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, in the Tier 3 model, the same variables (i.e. climate, soils, and management systems) are represented in considerably more detail both temporally and spatially, and exhibit multi-dimensional interactions through the more complex model structure.

(2) The IPCC Tier 1 and 2 methods have a simplified spatial resolution, where, in the United States, data is aggregated to climate and soil regions. In contrast, the Tier 3 model uses more than 300,000 individual NRI point locations in individual fields.

(3) The IPCC Tier 1 and 2 methods use simplified equilibrium step changes for changes in carbon emissions. In contrast, the Tier 3 approach simulates a continuous time period. More specifically, the DAYCENT model (i.e., daily time-step version of the Century model) simulates soil C dynamics (and CO_2 emissions and uptake) on a daily time step based on C emissions and removals from plant production and decomposition processes. These changes in soil C stocks are influenced by multiple sources 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 are simulated with DAYCENT based on the 2007 USDA NRI survey, in addition to information on irrigation (USDA-NRCS 2009). Additional sources of activity data were used to supplement the land-use information from NRI. The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity at the county level since 1989, with adjustments for long-term adoption of no-till agriculture (Towery 2001). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to cropland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 were used to adjust the area amended with manure (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area. Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. Nitrogen losses include direct N_2O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. For unmanaged systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil. More information on livestock manure production is available in the Manure Management, Section 5.2, and Annex 3.11.

Daily weather data were used as an input in the model simulations based on gridded data at a 32 km scale from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). Soil attributes were obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2005). The C dynamics at each NRI point was simulated 100 times as part of the uncertainty analysis, yielding a total of over 18 million simulation runs for the analysis. Uncertainty in the C stock estimates from DAYCENT associated with parameterization and model algorithms were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007, 2010). Carbon stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but C stock changes from 2008 to 2013 were assumed to be similar to 2007 for this Inventory due to a lack of activity data for these years. (Future Inventories will be updated with new activity data and the time series will be recalculated; see Planned Improvements section).

Tier 2 Approach

In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity were used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Major Land Resource Areas (MLRAs) formed the base spatial unit for conducting the Tier 2 analysis. MLRAs represent a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981). MLRAs were classified into climate regions according to the IPCC categories using the PRISM climate database of Daly et al. (1994), and the factors were assigned based on the land management systems in the MLRA in addition to the climate and soil types.

Reference C stocks were 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 provided a more robust sample for estimating the reference condition.

U.S.-specific stock change factors were derived from published literature to determine the impact of management practices on SOC storage (Ogle et al. 2003, Ogle et al. 2006). The factors include changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. U.S. factors associated with organic matter amendments were not estimated due to an insufficient number of studies in the United States to analyze the impacts. Instead, factors from IPCC (2003) were used to estimate the effect of those activities.

Activity data were primarily based on the historical land-use/management patterns recorded in the 2007 NRI (USDA-NRCS 2009). Each NRI point was classified by land use, soil type, climate region (using PRISM data, Daly et al. 1994) and management condition. Classification of cropland area by tillage practice was based on data from the Conservation Technology Information Center (CTIC 2004, Towery 2001) as described above. Activity data on wetland restoration of Conservation Reserve Program land were obtained from Euliss and Gleason (2002). Manure N amendments over the inventory time period were based on application rates and areas amended with manure N from Edmonds et al. (2003), in addition to the managed manure production data discussed in the methodology subsection for the Tier 3 analysis.

Combining information from these data sources, SOC stocks for mineral soils were estimated 50,000 times for 1982, 1992, 1997, 2002 and 2007, using a Monte Carlo stochastic simulation approach and probability distribution functions for U.S.-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2002, Ogle et al. 2003, Ogle et al. 2006). The annual C flux for 1990 through 1992 was determined by calculating the average annual change in stocks between 1982 and 1992; annual C flux for 1993 through 1997 was determined by calculating the average annual change in stocks between 1992 and 1997; annual C flux for 1998 through 2002 was determined by calculating the average annual change in stocks between 1998 and 2002; and annual C flux from 2003 through 2013 was determined by calculating the average annual change in stocks between 2003 and 2007.

Additional Mineral C Stock Change

Annual C flux estimates for mineral soils between 2008 and 2013 were adjusted to account for additional C stock changes associated with gains or losses in soil C after 2007 due to changes in CRP enrollment (USDA-FSA 2013). The change in enrollment relative to 2007 was based on data from USDA-FSA (2013) for 2008 through 2013. The differences in mineral soil areas were multiplied by 0.5 metric tons C per hectare per year to estimate the net effect on soil C stocks. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* were estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo Stochastic Simulation with 50,000 iterations. Emissions were based on the annual data from 1990 to 2007 for *Cropland Remaining Cropland* areas in the 2007 NRI (USDA-NRCS 2009). The annual emissions estimated for 2007 were applied to

2007 through 2013. (Future inventories will be updated with new activity data and the time series will be recalculated; see Planned Improvements section).

Uncertainty and Time-Series Consistency

Uncertainty associated with the *Cropland Remaining Cropland* land-use category was addressed for changes in agricultural soil C stocks (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-21 for each subsource (mineral soil C stocks and organic soil C stocks) and the method that was used in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.12 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with IPCC (2006). The combined uncertainty was 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 C stocks in *Cropland Remaining Cropland* ranged from 152 percent below to 154 percent above the 2013 stock change estimate of -23.4 MMT CO_2 Eq.

Table 6-21: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (MMT CO_2 Eq. and Percent)

Source	2013 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	(49.3)	(83.7)	(14.9)	-70%	70%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(2.8)	(5.1)	(0.9)	-80%	68%
Mineral Soil C Stocks: Cropland Remaining Cropland (Change in CRP enrollment relative to 2003)	6.6	3.3	9.9	-50%	50%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	22.1	14.0	32.5	-37%	47%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(23.4)**	**(59.0)**	**12.7**	**-152%**	**154%**

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of agricultural biomass and litter C stock changes. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land 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 significant changes in biomass C stocks, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C 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. However, this trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled throughout the inventory process. Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors. As discussed in the uncertainty section, results were compared to field measurements, and a statistical relationship was developed to assess uncertainties in the model's predictive capability. The comparisons included over 45 long-term experiments, representing about 800 combinations of management treatments across all of the sites (Ogle et al. 2007) (See Annex 3.12 for more information).

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements: 1) refining parameters associated with simulating crop production and carbon inputs to the soil in the DAYCENT biogeochemical model; 2) improving the model simulation of snow melt and water infiltration in soils; and 3) driving the DAYCENT simulations with updated input data for managed manure based on national livestock population. The change in SOC stocks increased by an average of 4.3 MMT CO_2 Eq. over the time series as a result of the improvements to the Inventory.

Planned Improvements

Two major planned improvements are underway. The first is to update the time series of land use and management data from the USDA NRI so that it is extended from 2008 through 2010 for both the Tier 2 and 3 methods (USDA-NRCS 2013). Fertilization and tillage activity data will also be updated as part of this improvement. The remote-sensing based data on the Enhanced Vegetation Index will be extended through 2010 in order to use the EVI data to drive crop production in DAYCENT. Overall, this improvement will extend the time series of activity data for the Tier 2 and 3 analyses through 2010.

The second major planned improvement is to analyze C stock changes on federal lands and Alaska for cropland and managed grassland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil C stock changes, but will be further refined over time to incorporate more of the management data.

Other improvements are planned for the DAYCENT biogeochemical model. Specifically, senescence events following grain filling in crops, such as wheat, will also be further evaluated and refined as needed.

An improvement is also underway to simulate crop residue burning in the DAYCENT based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (Section 5.5). This improvement will more accurately represent the C inputs to the soil that are associated with residue burning.

All of these improvements are expected to be completed for the 1990 through 2014 Inventory. However, the time line may be extended if there are insufficient resources to fund all or part of these planned improvements.

CO_2 Emissions from Agricultural Liming

IPCC (2006) recommends reporting CO_2 emissions from lime additions (in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to agricultural soils. Limestone and dolomite are added by land managers to increase soil pH (i.e., to reduce acidification). When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate and ultimate magnitude of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and the type of mineral applied. Emissions from liming of agricultural soils have fluctuated over the past 23 years, ranging from 3.7 MMT CO_2 Eq. to 5.9 MMT CO_2 Eq. In 2013, liming of agricultural soils in the United States resulted in emissions of 5.9 MMT CO_2 Eq. (1.6 MMT C), representing about a 27 percent increase in emissions since 1990 (see Table 6-22 and Table 6-23). The trend is driven entirely by the amount of lime and dolomite estimated to have been applied to soils over the time period.

Table 6-22: Emissions from Liming of Agricultural Soils (MMT CO_2 Eq.)

Source	1990		2005		2009	2010	2011	2012	2013
Limestone	4.1		3.9		3.4	4.3	3.4	4.3	4.4
Dolomite	0.6		0.4		0.3	0.5	0.4	1.5	1.5
Total[a]	**4.7**		**4.3**		**3.7**	**4.8**	**3.9**	**5.8**	**5.9**

[a] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements* as it is not currently possible to apportion the data by land-use category.
Note: Totals may not sum due to independent rounding.

Table 6-23: Emissions from Liming of Agricultural Soils (MMT C)

Source	1990	2005	2009	2010	2011	2012	2013
Limestone	1.1	1.1	0.9	1.2	0.9	1.2	1.2
Dolomite	0.2	0.1	0.1	0.1	0.1	0.4	0.4
Total[a]	**1.3**	**1.2**	**1.0**	**1.3**	**1.1**	**1.6**	**1.6**

[a] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements* as it is not currently possible to apportion the data by land-use category.
Note: Totals may not sum due to independent rounding.

Methodology

CO_2 emissions from degradation of limestone and dolomite applied to agricultural soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite applied (see Table 6-24) were multiplied by CO_2 emission factors from West and McBride (2005). These 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 agricultural lime that may leach through the soil and travel by rivers to the ocean (West and McBride 2005). This analysis of lime dissolution is based on liming occurring in the Mississippi River basin, where the vast majority of all U.S. liming takes place (West 2008). U.S. liming that does not occur in the Mississippi River basin tends to occur under similar soil and rainfall regimes, and, thus, the emission factor is appropriate for use across the United States (West 2008). The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993 through 2006; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a and 2014; USGS 2008 through 2014). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying crushed stone manufacturers. Because some manufacturers were reluctant to provide information, 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 6-5: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of agricultural soils were estimated using a Tier 2 methodology based on liming emission factors specific to the United States that are lower than the IPCC (2006) emission default factors, and are specific to U.S. soil conditions under which liming occurs. For example, as described previously, most liming 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 such soil conditions, a significant portion of dissolved agricultural lime is predicted to leach through the soil and travels by rivers to the ocean, the majority of which is then predicted to precipitate in the ocean as $CaCO_3$ (West and McBride 2005). Therefore, the U.S. specific emissions 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 2013 U.S. emissions from liming of agricultural soils are 5.9 MMT CO_2 Eq. using the U.S.-specific, West and McBride (2005) emission factors and 12.0 MMT CO_2 Eq. using the IPCC (2006) emission factors.

The “unspecified” and “estimated” amounts of crushed limestone and dolomite applied to agricultural soils were calculated by multiplying the percentage of total “specified” limestone and dolomite production applied to agricultural 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 agricultural soils (as opposed to other uses of the stone) was assumed to be proportionate to the amount of “specified” crushed limestone and dolomite that was applied to agricultural soils. In addition, data were not available for 1990, 1992, and 2013 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 2013 data, 2012 fractions were applied to a 2013 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2014* (USGS 2014).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the USGS from 1995 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. Since limestone and dolomite activity data are also available at the state level, the national-level estimates reported here were broken out by state, although state-level estimates are not reported here. Also, it is important to note that all emissions from liming are accounted for under *Cropland Remaining Cropland* because it is not currently possible to apportion the data to each agricultural land-use category (i.e., *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements*). The majority of liming in the United States occurs on *Cropland Remaining Cropland.*

Table 6-24: Applied Minerals (MMT)

Mineral	1990	2005	2009	2010	2011	2012	2013
Limestone[a]	19.0	18.1	15.7	20.0	15.9	19.9	20.4
Dolomite[a]	2.4	1.9	1.2	1.9	1.9	6.3	6.4

[a] Data represent amounts applied to *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements* as it is not currently possible to apportion the data by land-use category.

Uncertainty and Time-Series Consistency

Uncertainty regarding limestone and dolomite activity data inputs was estimated at ±15 percent and assumed to be uniformly distributed around the inventory estimate (Tepordei 2003, Willett 2013b). Analysis of the uncertainty associated with the emission factors included the following: the fraction of agricultural 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 accounted for, but should not change the uncertainty associated with CO_2 emissions (West 2005). The uncertainties associated with the fraction of agricultural lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were each modeled as a smoothed triangular distribution between ranges of zero percent to 100 percent. The uncertainty surrounding these two components largely drives the overall uncertainty estimates reported below. More information on the uncertainty estimates for Liming of Agricultural Soils is contained within the Uncertainty Annex.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 emissions from liming of agricultural soils. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-25. CO_2 emissions from Liming of Agricultural Soils in 2013 were estimated to be between 0.7 and 12.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 88 percent below to 103 percent above the 2013 emission estimate of 5.9 MMT CO_2 Eq.

Table 6-25: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming of Agricultural Soils (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Liming of Agricultural Soils[b]	CO_2	5.9	0.7	12.1	-88%	103%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements* as it is not currently possible to apportion the data by land-use category.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for Liming was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing the magnitude of emission factors historically to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

Several adjustments were made in the current Inventory to improve the results. In the previous Inventory, to estimate 2012 data, 2011 fractions were applied to a 2012 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2013* (USGS 2013). Since publication of the previous Inventory, the *Minerals Yearbook* has published actual quantities of crushed stone sold or used by producers in the United States in 2012. These values have replaced those used in the previous Inventory to calculate the quantity of minerals applied to soil and the emissions from liming of agricultural soils. Compared to the estimates used in the previous Inventory for 2012, the updated activity data for 2012 are approximately 3.8 MMT greater for limestone, and approximately 4.4 MMT greater for dolomite. As a result, the reported emissions from liming of agricultural soils for 2012 increased by about 47 percent.

CO_2 Emissions from Urea Fertilization

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to CO_2 emissions through the release of CO_2 that was fixed during the industrial production process. In the presence of water and urease enzymes, urea 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 totaled 4.0 MMT CO_2 Eq. (1.1 MMT C) in 2013 (Table 6-26 and Table 6-27). Due to an increase in the use of urea as a fertilizer, emissions from urea have increased 66 percent between 1990 and 2013.

Table 6-26: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2009	2010	2011	2012	2013
Urea Fertilization[a]	2.4	3.5	3.6	3.8	4.1	4.2	4.0

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, and *Forest Land Remaining Forest Land* because it is not currently possible to apportion the data by land-use category.

Table 6-27: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2009	2010	2011	2012	2013
Urea Fertilization[a]	0.7	1.0	1.0	1.0	1.1	1.2	1.1

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[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, and *Forest Land Remaining Forest Land* because it is not currently possible to apportion the data by land-use category.

Methodology

CO_2 emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The annual amounts of urea applied to croplands (see Table 6-28) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2014). These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of C per metric ton of urea), which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July previous year through June current year), 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. For example, for the 2000 fertilizer year, 35 percent of the fertilizer was applied in July through December 1999, and 65 percent was applied in January through June 2000. Fertilizer sales data for the 2013 fertilizer year (i.e., July 2012 through June 2013) were not available in time for publication. Accordingly, urea application in the 2013 fertilizer year was estimated using a linear, least squares trend of consumption over the previous five years (2008 through 2012). A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-state and inter-annual variability in consumption. First, January through June 2013 urea consumption was estimated using the approach described above, after which the percentage change in use from the previous year (i.e., January through June 2012) was determined. Next, the July through December 2012 data was multiplied by the same percent change to estimate the July through December 2013 urea consumption (assuming a constant percentage change between 2012 and 2013). 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. Since urea activity data are also available at the state level, the national-level estimates reported here were broken out by state, although state-level estimates are not reported here. Also, it is important to note that all emissions from urea fertilization are accounted for under *Cropland Remaining Cropland* because it is not currently possible to apportion the data to each agricultural land-use category (i.e., *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements*). The majority of urea fertilization in the United States occurs on *Cropland Remaining Cropland.*

Table 6-28: Applied Urea (MMT)

	1990		2005		2009	2010	2011	2012	2013
Urea Fertilizer[a]	3.3		4.8		4.8	5.2	5.6	5.8	5.5

[a] These numbers represent amounts applied to all agricultural land, including *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements*, and *Forest Land Remaining Forest Land* because it is not currently possible to apportion the data by land-use category.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 6-29 for Urea Fertilization. An Approach 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C in $CO(NH_2)_2$ applied to soils is ultimately emitted into the environment as CO_2. This factor does not incorporate the possibility that some of the C may be retained in the soil. The emission estimate is, therefore, likely to be an overestimate. In addition, each urea consumption data point has an associated uncertainty. Urea for non-fertilizer use, such as aircraft deicing, may be included in consumption totals; it was determined through personal communication with Fertilizer Regulatory Program Coordinator David L. Terry (2007), however, that this amount is most likely very small. Research into aircraft deicing practices also confirmed that urea is used minimally in the industry; a 1992 survey found a known annual usage of approximately 2,000 tons of urea for deicing; this would constitute 0.06 percent of the 1992 consumption of urea (EPA 2000). Similarly, surveys conducted from 2002 to 2005 indicate that total urea use for deicing at U.S. airports is estimated to be 3,740 metric tons per year, or less than 0.07 percent of the fertilizer total for 2007 (Itle 2009). Lastly, there is uncertainty surrounding the assumptions behind the calculation that converts fertilizer years to calendar years. CO_2 emissions from urea fertilization of agricultural soils in 2013 were estimated to be between 2.3 and 4.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 42 percent below to 3 percent above the 2013 emission estimate of 4.0 MMT CO_2 Eq.

Table 6-29: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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	4.0	2.3	4.1	-42%	3%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for Urea was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing the magnitude of emission factors historically to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

In the current Inventory, the 2011 and 2012 emissions estimates were updated to reflect the urea application reported in the *Commercial Fertilizers Report* for the 2012 fertilizer year (July through December 2011, January through June, 2012). Specifically, the 2011 emissions estimates were revised to reflect the July to December 2011 urea application data. This recalculation resulted in actual emissions that are 3 percent higher than the previously estimated 2011 emissions. For 2012, the January through June, 2012 actual urea application rates were used to replace the estimates from the previous year, and the July through December rates of application were estimated using the methodology described above (i.e., the July through December, 2011 urea rates were multiplied by the percentage change in rates from January through June, 2011 to January through June, 2012). The updated activity data for 2012 are approximately 1,068 kt greater than the amount estimated for 2012 in the previous Inventory. As a result, the reported emissions from urea for 2012 in the current Inventory are 23 percent higher than the estimated emission reported for 2012 in the previous Inventory.

Planned Improvements

The primary planned improvement is to investigate using a Tier 2 or Tier 3 approach, which would utilize country-specific information to estimate a more precise emission factor. This possibility was investigated for the current Inventory, but no options were identified for updating to a Tier 2 or Tier 3 approach.

6.5 Land Converted to Cropland (IPCC Source Category 4B2)

Land Converted to Cropland includes all cropland in an Inventory year that had been in another land use(s) during the previous 20 years[38] (USDA-NRCS 2009). For example, grassland or forestland 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 in the IPCC guidelines (IPCC 2006). This Inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but does not include the approximately 100,000 hectares of *Land Converted to Cropland* on federal lands and a minor amount of *Land Converted to Cropland* in Alaska. Consequently there is a discrepancy between the total amount of managed area in *Land Converted to Cropland* (see Section 6.1) and the cropland area included in the Inventory. Improvements are underway to include federal croplands in future C inventories.

Background on agricultural carbon (C) stock changes is provided in section 6.4 *Cropland Remaining Cropland* and therefore will only be briefly summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for long-term storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils, with the exception of C stored in perennial woody crop biomass. The IPCC (2006) guidelines recommend reporting changes in soil organic carbon (SOC) stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[39]

Land use and management of mineral soils in *Land Converted to Cropland* was the largest contributor to C loss throughout the time series, accounting for approximately 70 percent of the emissions in the category (Table 6-30 and Table 6-31). The conversion of grassland to cropland was the largest source of soil C loss (accounting for approximately 65 percent of the emissions in the category), though losses declined over the time series. The net flux of C from soil stock changes in 2013 was 16.1 MMT CO_2 Eq. (4.4 MMT C) in 2013, including 11.3 MMT CO_2 Eq. (3.1 MMT C) from mineral soils and 4.8 MMT CO_2 Eq. (1.3 MMT C) from drainage and cultivation of organic soils.

Table 6-30: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* by Land Use Change Category (MMT CO_2 Eq.)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Grassland Converted to Cropland							
Mineral	20.0	14.0	10.6	10.6	10.6	10.5	10.6
Organic	2.5	4.3	4.0	4.0	4.0	4.0	4.0
Forest Converted to Cropland							
Mineral	1.5	0.3	0.3	0.3	0.3	0.3	0.3
Organic	(0.2)	0.3	0.2	0.2	0.2	0.2	0.2
Other Lands Converted Cropland							
Mineral	0.3	0.1	0.1	0.1	0.1	0.1	0.1
Organic	+	+	+	+	+	+	+
Settlements Converted Cropland							
Mineral	0.6	0.3	0.3	0.3	0.3	0.3	0.3
Organic	+	0.2	0.2	0.2	0.2	0.2	0.2
Wetlands Converted Cropland							
Mineral	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Organic	(0.2)	0.3	0.4	0.4	0.4	0.4	0.4
Total Mineral Soil Flux	**22.4**	**14.8**	**11.4**	**11.4**	**11.4**	**11.3**	**11.3**

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[38] The 2009 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently the classifications from 1990 to 2001 were based on less than 20 years.

[39] CO_2 emissions associated with liming urea fertilization are also estimated but included in 7.4 *Cropland Remaining Cropland*.

Total Organic Soil Flux	**2.1**	**5.1**	**4.8**	**4.8**	**4.8**	**4.8**	**4.8**
Total Net Flux	**24.5**	**19.8**	**16.2**	**16.2**	**16.2**	**16.1**	**16.1**

Note: Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series.
+ Does not exceed 0.05 MMT CO_2 Eq.

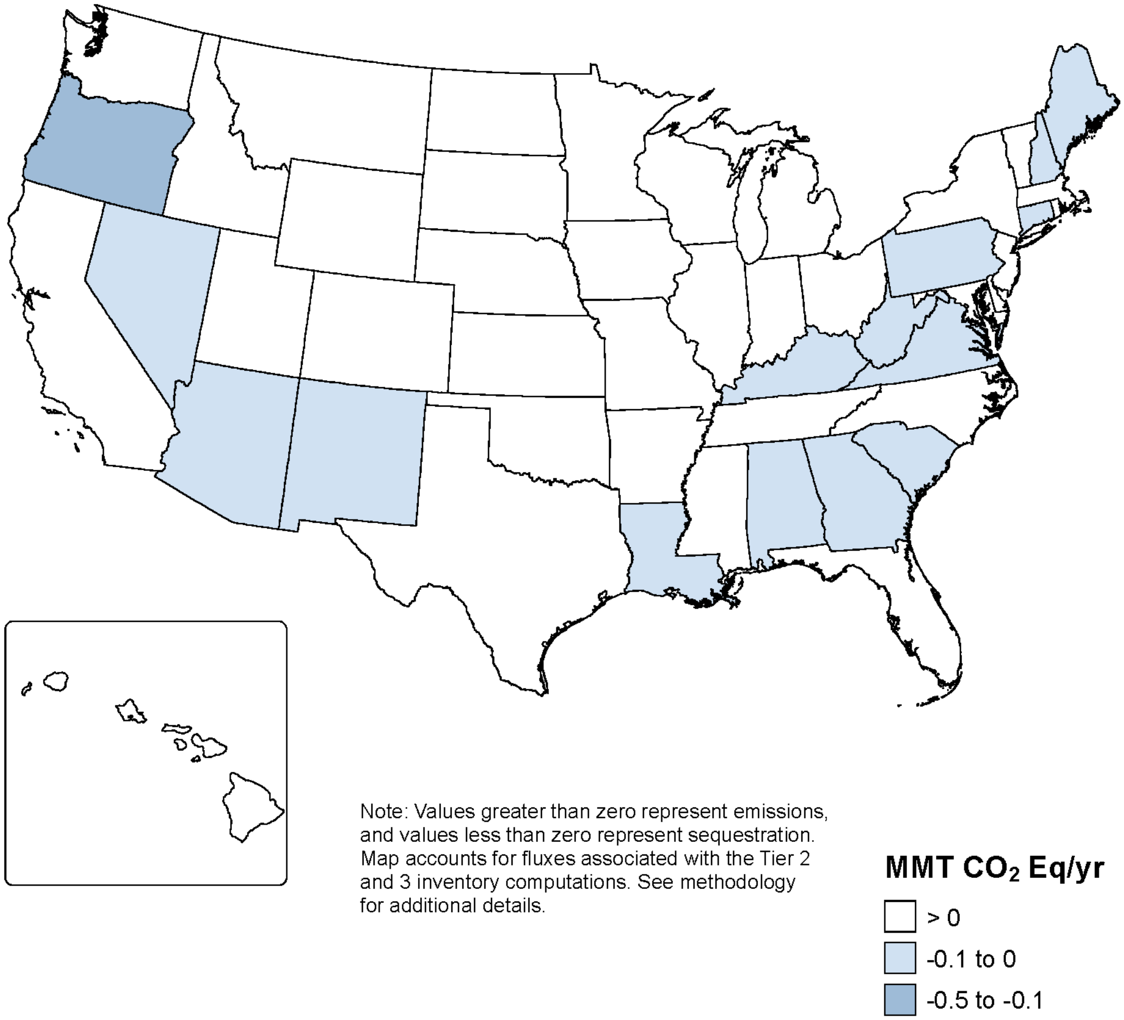
Table 6-31: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (MMT C)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Grassland Converted to Cropland							
Mineral	5.4	3.8	2.9	2.9	2.9	2.9	2.9
Organic	0.7	1.2	1.1	1.1	1.1	1.1	1.1
Forest Converted to Cropland							
Mineral	0.4	0.1	0.1	0.1	0.1	0.1	0.1
Organic	(0.1)	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted Cropland							
Mineral	0.1	+	+	+	+	+	+
Organic	+	+	+	+	+	+	+
Settlements Converted Cropland							
Mineral	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Organic	+	0.1	+	+	+	+	+
Wetlands Converted Cropland							
Mineral	0.1	+	+	+	+	+	+
Organic	(0.1)	0.1	0.1	0.1	0.1	0.1	0.1
Total Mineral Soil Flux	**6.1**	**4.0**	**3.1**	**3.1**	**3.1**	**3.1**	**3.1**
Total Organic Soil Flux	**0.6**	**1.4**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Total Net Flux	**6.7**	**5.4**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**

Note: Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series.
+ Does not exceed 0.05 MMT C
Parentheses indicate net sequestration.

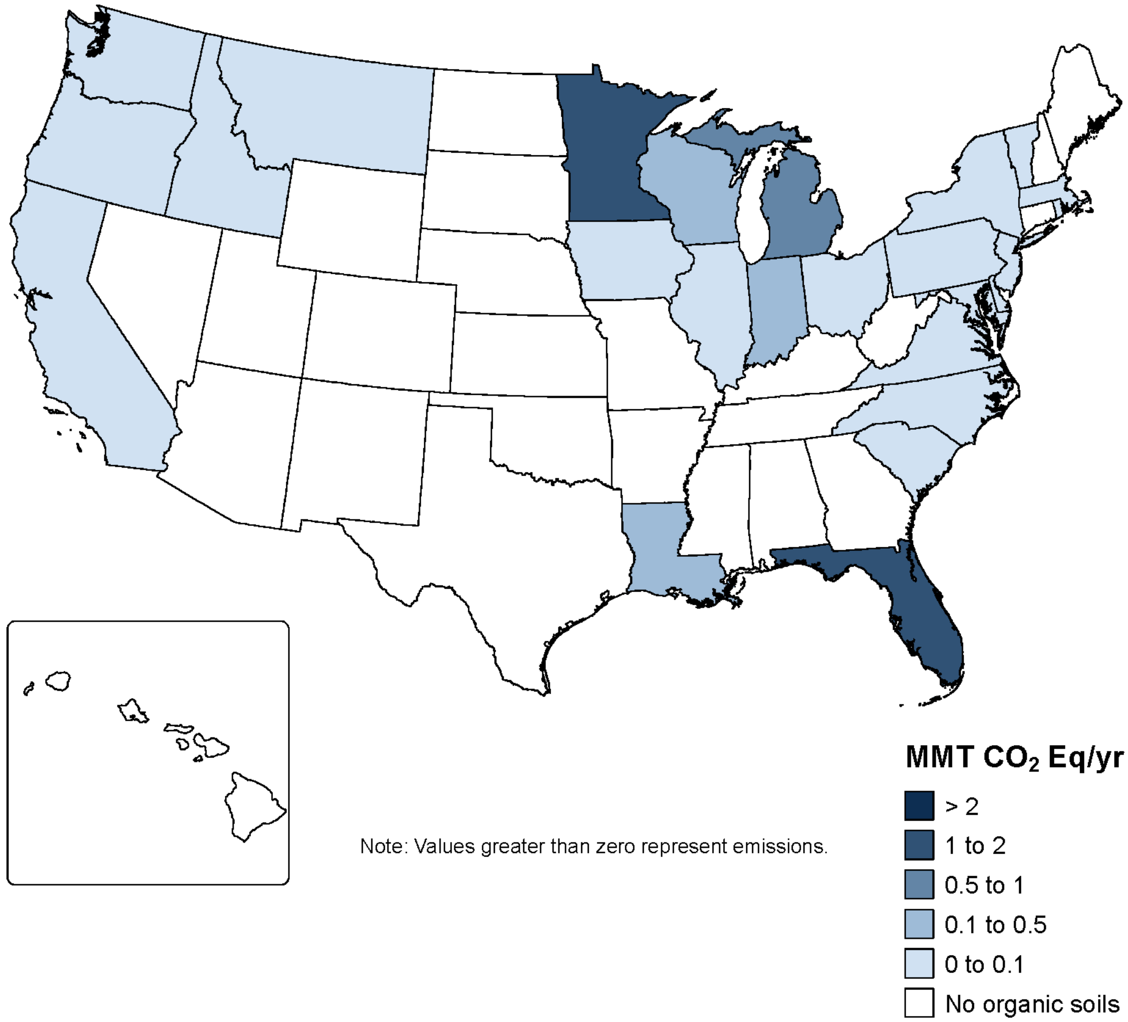
The spatial variability in the 2013 annual flux in CO_2 from mineral soils is displayed in Figure 6-10 and from organic soils in Figure 6-11. Losses occurred in most regions of the United States. In particular, conversion of grassland and forestland to cropland led to enhanced decomposition of soil organic matter and a net loss of C from the soil pool. The regions with the highest rates of emissions from organic soils coincide with the largest concentrations of organic soils used for agricultural production, including Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California).

Figure 6-10: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2013, *Land Converted to Cropland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See methodology for additional details.

Figure 6-11: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2013, *Land Converted to Cropland*



Note: Values greater than zero represent emissions.

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks for *Land Converted to Cropland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils Biomass and litter C stock changes associated with conversion of forest to cropland are not explicitly included in this category, but are included in the *Forest Land Remaining Forest Land* section. Further elaboration on the methodologies and data used to estimate stock changes for mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil C stock changes were estimated for *Land Converted to Cropland* according to land-use histories recorded in the 2007 USDA NRI survey (USDA-NRCS 2009). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and data are currently available through 2010 (USDA-NRCS 2013). However, this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory. NRI points were classified as *Land Converted to Cropland* in a given year between 1990 and 2007 if the land use was cropland but had been another use during the previous 20 years. Cropland includes all land used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) was applied to estimate C stock changes for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. Soil C stock changes on the remaining soils were estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables, tobacco, 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 forest or federal ownership.[40]

Tier 3 Approach

For the Tier 3 method, mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical[41] model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DAYCENT model utilizes the soil C 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 were obtained by using the model to simulate historical land-use change patterns as recorded in the USDA NRI (USDA-NRCS 2009). C stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but C stock changes from 2008 to 2013 were assumed to be similar to 2007 due to a lack of activity data for these years. (Future inventories will be updated with new activity data and the time series will be recalculated; See Planned Improvements section in *Cropland Remaining Cropland*). The methods used for *Land Converted to Cropland* are the same as those described in the Tier 3 portion of *Cropland Remaining Cropland* section for mineral soils.

Tier 2 Approach

For the mineral soils not included in the Tier 3 analysis, SOC stock changes were estimated using a Tier 2 Approach for *Land Converted to Cropland* as described in the Tier 2 portion of the *Cropland Remaining Cropland* section for mineral soils.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies were based on the same method described for *Cropland Remaining Cropland*. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* was estimated using Tier 2, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-32 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) and method that was used in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.12 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with 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 soil C stocks in *Land Converted to Cropland* ranged from 72 percent below to 81 percent above the 2013 stock change estimate of 16.1 MMT CO_2 Eq.

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[40] Federal land is not a land use, but rather an ownership designation that is treated as forest or nominal grassland for purposes of these calculations. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2009).

[41] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

Table 6-32: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Cropland* (MMT CO_2 Eq. and Percent)

Source	2013 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	**14.6**	**3.0**	**27.7**	**-80%**	**90%**
Mineral Soil C Stocks: Tier 3	9.8	(1.3)	20.9	-114%	114%
Mineral Soil C Stocks: Tier 2	0.8	0.4	1.2	-49%	54%
Organic Soil C Stocks: Tier 2	4.0	0.7	10.9	-83%	172%
Forests Converted to Cropland	**0.5**	**0.2**	**1.1**	**-53%**	**123%**
Mineral Soil C Stocks: Tier 2	0.3	0.1	0.4	-49%	54%
Organic Soil C Stocks: Tier 2	0.2	0.0	0.8	-100%	258%
Other Lands Converted to Cropland	**0.1**	**0.1**	**0.2**	**-49%**	**54%**
Mineral Soil C Stocks: Tier 2	0.1	0.1	0.2	-49%	54%
Organic Soil C Stocks: Tier 2	NA	NA	NA	NA	NA
Settlements Converted to Cropland	**0.5**	**0.3**	**0.7**	**-36%**	**41%**
Mineral Soil C Stocks: Tier 2	0.3	0.2	0.5	-49%	54%
Organic Soil C Stocks: Tier 2	0.2	0.1	0.3	-46%	63%
Wetlands Converted to Croplands	**0.4**	**0.2**	**0.7**	**-45%**	**57%**
Mineral Soil C Stocks: Tier 2	0.1	0.04	0.1	-49%	54%
Organic Soil C Stocks: Tier 2	0.4	0.2	0.6	-53%	68%
Total: Land Converted to Cropland	**16.1**	**4.5**	**29.2**	**-72%**	**81%**
Mineral Soil C Stocks: Tier 3	**9.8**	**(1.3)**	**20.9**	**-114%**	**114%**
Mineral Soil C Stocks: Tier 2	**1.6**	**1.1**	**2.0**	**-28%**	**31%**
Organic Soil C Stocks: Tier 2	**4.8**	**1.4**	**11.7**	**-70%**	**145%**

Note: Parentheses indicate negative values or net sequestration.

NA: Other land by definition does not include organic soil (see Section 6.1—Representation of the U.S. Land Base). Consequently, no land areas, C stock changes, or uncertainty results are estimated for land use conversions from Other lands to Croplands and Other lands to Grasslands on organic soils.

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of agricultural biomass and litter C stock changes other than the loss of forest biomass and litter, which is reported in the *Forest Land Remaining Forest Land* section of this report. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land 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 significant changes in biomass C stocks, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C 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. However, this trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements: 1) refining parameters associated with simulating crop production and carbon inputs to the soil in the DAYCENT biogeochemical model; 2) improving the model simulation of snow melt and water infiltration in soils; and 3) driving the DAYCENT simulations with updated input data for the excretion of C and N onto Pasture/Range/Paddock and N additions from managed manure based on national livestock population. Change in SOC stocks declined by an average of 0.9 MMT CO_2 Eq. over the time series as a result of these improvements to the Inventory.

QA/QC and Verification

See QA/QC and Verification section under *Cropland Remaining Cropland*.

Planned Improvements

Soil C stock changes with land use conversion from forest land to cropland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and croplands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to cropland. This planned improvement may not be fully implemented for two more years, depending on resource availability. Additional planned improvements are discussed in the *Cropland Remaining Cropland* section.

6.6 Grassland Remaining Grassland (IPCC Source Category 4C1)

Grassland Remaining Grassland includes all grassland in an Inventory year that had been classified as grassland for the previous 20 years[42] (USDA-NRCS 2009). Grassland includes pasture and rangeland that are primarily 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 interseeding of legumes. This Inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not include the 75 million hectares of *Grassland Remaining Grassland* on federal lands or the 36 million hectares of *Grassland Remaining Grassland* in Alaska. This leads to a discrepancy with the total amount of managed area in *Grassland Remaining Grassland* (see Section 6.1 — Representation of the U.S. Land Base) and the grassland area included in the *Grassland Remaining Grassland* (IPCC Source Category 4C1—Section 6.6).

Background on agricultural carbon (C) stock changes is provided in the section 6.4, *Cropland Remaining Cropland*, and will only be summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for longer-term storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared to the soil C pool, with the exception of C stored in tree and shrub biomass that occurs in grasslands. The IPCC (2006) guidelines recommend reporting changes in soil organic C (SOC) stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[43]

In *Grassland Remaining Grassland*, there has been considerable variation in soil C flux between 1990 and 2013. These changes are driven by variability in weather patterns and associated interaction with land management activity. Even in the years with larger total changes in stocks, changes remain small on a per hectare rate. Land use and management increased soil C in mineral soils of *Grassland Remaining Grassland* between 1990 and 2006, after which the trend was reversed to small declines in soil C. In contrast, organic soils have lost relatively small amounts of C annually from 1990 through 2013. While the overall trend was a gain in soil C in *Grassland Remaining Grassland* from 1990 to 2003, the last decade has seen small losses in soil C during most years (Table 6-33 and Table 6-34). Overall, from 1990 to 2013, the net change in soil C flux increased by 14.0 MMT CO_2 Eq. (3.8 MMT C). Current estimates for flux from soil C stock changes in 2013 are estimated at a total of 12.1 MMT CO_2 Eq. (3.3

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[42] The 2009 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently the classifications from 1990 to 2001 were based on less than 20 years

[43] CO_2 emissions associated with liming and urea fertilization are also estimated but included in 6.4 Cropland Remaining Cropland.

MMT C), with 9.1 MMT CO_2 Eq. (2.5 MMT C) from mineral soils and 3.0 MMT CO_2 Eq. (0.8 MMT C) from organic soils.

Table 6-33: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Mineral Soils	(6.5)	1.2	8.7	8.7	8.7	8.5	9.1
Organic Soils	4.6	3.1	3.0	3.0	3.0	3.0	3.0
Total Net Flux	**(1.9)**	**4.2**	**11.7**	**11.7**	**11.7**	**11.5**	**12.1**

Note: Totals may not sum due to independent rounding. Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series. Parentheses indicate net sequestration.

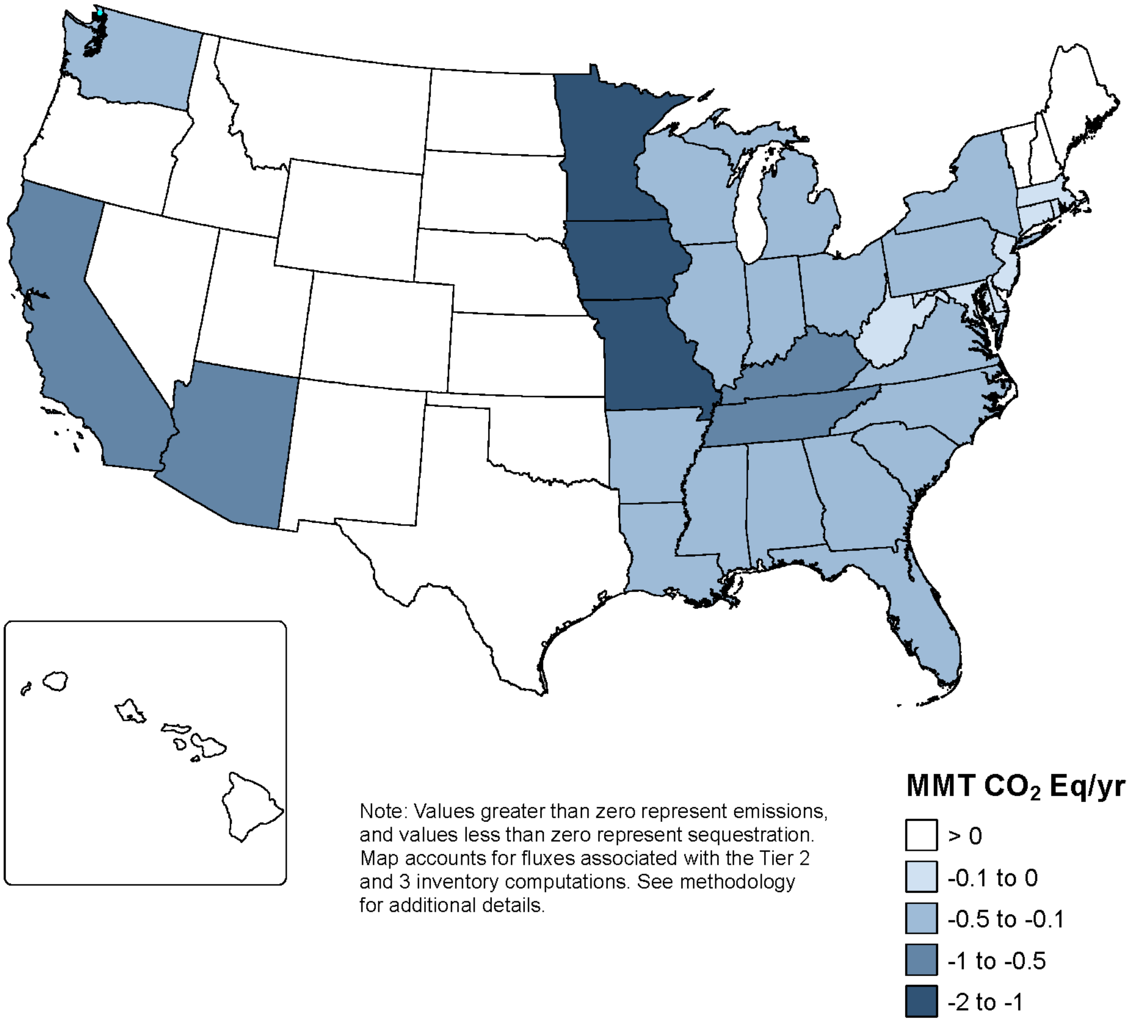
Table 6-34: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT C)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Mineral Soils	(1.8)	0.3	2.4	2.4	2.4	2.3	2.5
Organic Soils	1.3	0.8	0.8	0.8	0.8	0.8	0.8
Total Net Flux	**(0.5)**	**1.2**	**3.2**	**3.2**	**3.2**	**3.1**	**3.3**

Note: Totals may not sum due to independent rounding. Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series. Parentheses indicate net sequestration.

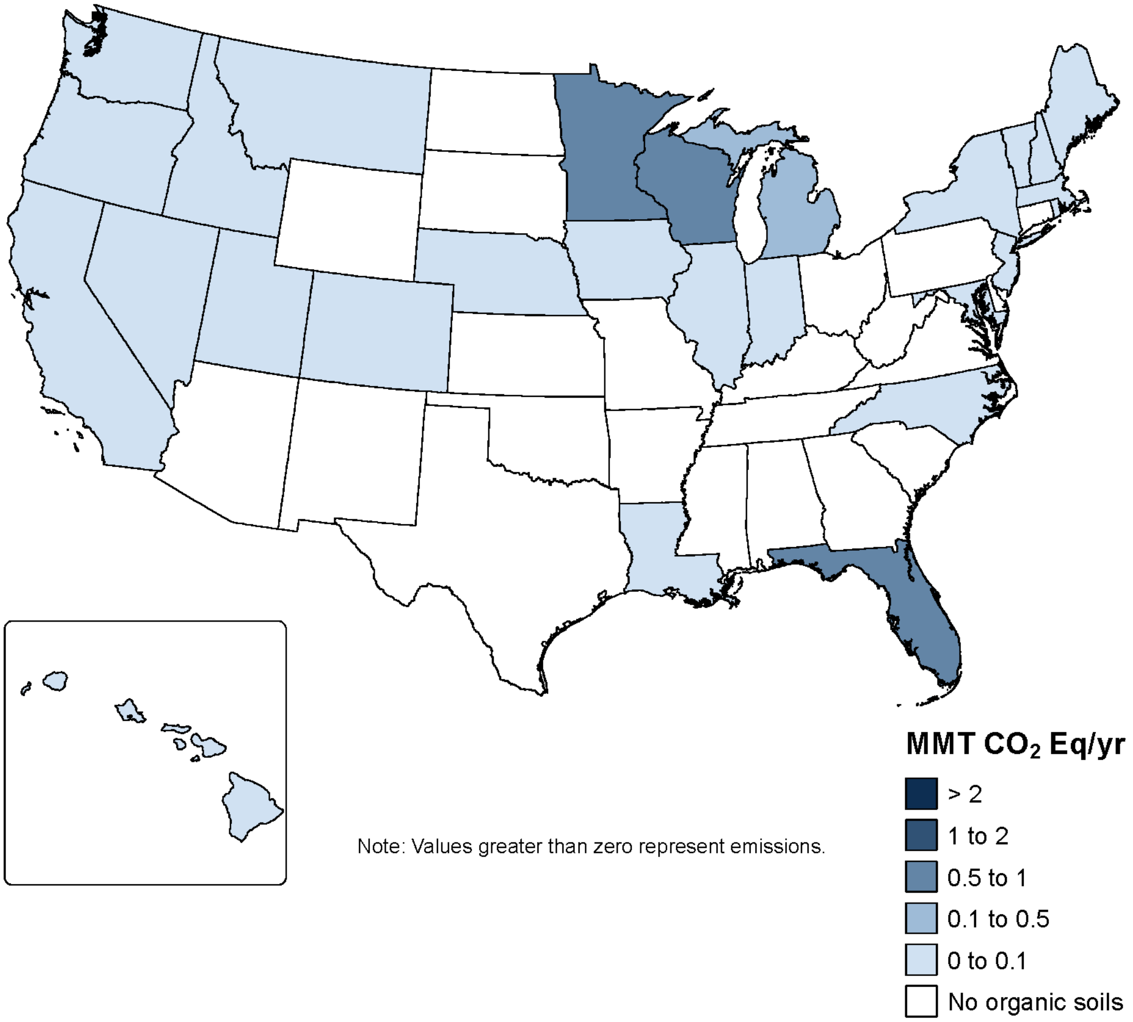
The spatial variability in the 2013 annual flux in CO_2 from mineral is displayed in Figure 6-12 and organic soils in Figure 6-13. Although relatively small on a per-hectare basis, grassland gained soil C in several regions during 2013, including the Northeast, Southeast, portions of the Midwest, and Pacific Coastal Region. The regions with the highest rates of emissions from organic soils coincide with the largest concentrations of organic soils used for managed grassland, including the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California).

Figure 6-12: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2013, *Grassland Remaining Grassland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See methodology for additional details.

Figure 6-13: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2013, *Grassland Remaining Grassland*



Note: Values greater than zero represent emissions.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C 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 are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil C stock changes were estimated for *Grassland Remaining Grassland* according to land use histories recorded in the 2007 USDA NRI survey (USDA-NRCS 2009). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program initiated annual data collection, and the annual data are currently available through 2010 (USDA-NRCS 2013). However, this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory. NRI points were classified as *Grassland Remaining Grassland* in a given year between 1990 and 2007 if the land use had been grassland for 20 years.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) was applied to estimate C stock changes for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils were estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume) and additional stock changes associated with sewage sludge amendments.

Tier 3 Approach

Mineral SOC stocks and stock changes for *Grassland Remaining Grassland* were estimated using the DAYCENT biogeochemical[44] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in *Cropland Remaining Cropland*. The DAYCENT model utilizes the soil C 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 and management patterns were used in the DAYCENT simulations as recorded in the USDA NRI survey, with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) and National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to grassland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds, et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 were used to adjust the area amended with manure (see *Cropland Remaining Cropland* for further details). Greater availability of managed manure nitrogen (N) relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area.

The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems based on methods described in *Manure Management*, Section 5.2, and Annex 3.11. Manure N deposition from grazing animals (i.e., PRP manure) was an input to the DAYCENT model (see Annex 3.11), and included approximately 91 percent of total PRP manure (the remainder is deposited on federal lands, which are not included in this Inventory). C stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but C stock changes from 2008 to 2013 were assumed to be similar to 2007 due to a lack of activity data for these years. (Future inventories will be updated with new activity data and the time series will be recalculated; See Planned Improvements section in *Cropland Remaining Cropland*). The methods used for *Grassland remaining Grassland* are the same as those described in the Tier 3 portion of *Cropland Remaining Cropland* section for mineral soils.

Tier 2 Approach

The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils.

Additional Mineral C Stock Change Calculations

A Tier 2 method was used to adjust annual C flux estimates for mineral soils between 1990 and 2013 to account for additional C stock changes associated with sewage sludge amendments. Estimates of the amounts of sewage sludge N applied to agricultural land were derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from EPA (1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. N application rates from Kellogg et al. (2000) were used to determine the amount of area receiving sludge amendments. Although sewage sludge can be added to land managed for other land uses, it was assumed that agricultural amendments occur in grassland. Cropland is not likely to be amended with sewage sludge due to the high metal content and other pollutants in human waste. The soil C storage rate was estimated at

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[44] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

0.38 metric tons C per hectare per year for sewage sludge amendments to grassland. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* were estimated using the Tier 2 method provided in IPCC (2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 6-35 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.12 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with 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 soil C stocks in *Grassland Remaining Grassland* ranged from 297 percent below to 297 percent above the 2013 stock change estimate of 12.1 MMT CO_2 Eq. The large relative uncertainty is due to the small net flux estimate in 2013.

Table 6-35: Approach 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within *Grassland Remaining Grassland* (MMT CO_2 Eq. and Percent)

Source	2013 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 Grassland Remaining Grassland, Tier 3 Methodology	10.3	(25.5)	46.2	-347%	347%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	0.1	0.0	0.2	-86%	109%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Sewage Sludge Amendments)	(1.4)	(2.1)	(0.7)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	3.0	1.6	4.9	-46%	63%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Grassland Remaining Grassland	**12.1**	**(23.8)**	**48.0**	**-297%**	**297%**

Note: Parentheses indicate negative values.

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Uncertainty is also associated with a lack of reporting on agricultural biomass and litter C stock changes and non-CO_2 greenhouse gas emissions from burning. Biomass C stock changes may be significant for managed grasslands with woody encroachment that has not attained enough tree cover to be considered forest lands. Grassland burning is not as common in the United States as in other regions of the world, but fires do occur through both natural ignition sources and prescribed burning. Changes in litter C stocks are assumed to be negligible in grasslands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled through the inventory process. In the previous Inventory, DAYCENT was used to simulate the PRP manure N input with automated routines, but errors occurred leading to a mismatch between the amount of manure N excreted according to the *Manure Management* data, relative to the amount simulated in DAYCENT. This error appears to be corrected based on internal checks, and should provide internal consistency between the *Manure Management* data and the *Agricultural Soil Management* and LULUCF inventories.

Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors. Modeled results were compared to measurements from several long-term grazing experiments (see Annex 3.12 for more information).

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements, including 1) improving the model simulation of snow melt and water infiltration in soils; and 2) driving the DAYCENT simulations with updated input data for the excretion of C and N onto Pasture/Range/Paddock and N additions from managed manure based on national livestock population. As a result of these improvements to the Inventory, changes in SOC stocks declined by an average of 1.76 MMT CO_2 eq. annually over the time series.

Planned Improvements

One of the key planned improvements for *Grassland Remaining Grassland* is to develop an inventory of carbon stock changes for the 75 million hectares of federal grasslands in the western United States. While federal grasslands likely have minimal changes in land management and C stocks, improvements are underway to include these grasslands in future C Inventories. Grasslands in Alaska will also be further evaluated in the future. This is a significant improvement and estimates are expected to be available for the 1990-2014 Inventory. Another key planned improvement is to estimate non-CO_2 greenhouse gas emissions from burning of grasslands. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland*.

6.7 Land Converted to Grassland (IPCC Source Category 4C2)

Land Converted to Grassland includes all grassland in an Inventory year that had been in another land use(s) during the previous 20 years[45] (USDA-NRCS 2009). For example, cropland or forestland 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 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. This Inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not but does not include the 800,000 to 850,000 hectares of *Land Converted to Grassland* on federal lands or *Land Converted to Grassland* in Alaska. Consequently there is a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Section 6.1—Representation of the U.S. Land Base) and the grassland area included in *Land Converted to Grassland* (IPCC Source Category 4C2—Section 6.7).

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[45] The 2009 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently the classifications from 1990 to 2001 were based on less than 20 years.

Background on agricultural carbon (C) stock changes is provided in *Cropland Remaining Cropland* and therefore will only be briefly summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for long-term storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils, with the exception of C stored in tree and shrub biomass that occurs in grasslands. IPCC (2006) recommend reporting changes in soil organic C (SOC) stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[46]

Land use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks between 1990 and 2013 (see Table 6-36 and Table 6-37). The net C flux from soil C stock changes for mineral soils between 1990 and 2013 led to a decrease of 1.7 MMT CO_2 Eq. (0.5 MMT C) in the atmosphere. In contrast, over the same period, drainage of organic soils for grassland management led to an increase in C emissions to the atmosphere of 0.3 MMT CO_2 Eq. (0.1 MMT C). The flux associated with soil C stock changes in 2013 is estimated at a net uptake of 8.8 MMT CO_2 Eq. (-2.4 MMT C) from the atmosphere.

Table 6-36: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Cropland Converted to Grassland							
Mineral	(6.4)	(9.0)	(8.8)	(8.8)	(8.7)	(8.6)	(8.6)
Organic	0.5	1.0	0.9	0.9	0.9	0.9	0.9
Forest Converted to Grassland							
Mineral	(1.1)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Organic	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted Grassland							
Mineral	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic	+	+	+	+	+	+	+
Settlements Converted Grassland							
Mineral	(0.4)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Organic	+	+	+	+	+	+	+
Wetlands Converted Grassland							
Mineral	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total Mineral Soil Flux	**(8.2)**	**(10.3)**	**(10.0)**	**(10.0)**	**(10.0)**	**(9.9)**	**(9.9)**
Total Organic Soil Flux	**0.8**	**1.3**	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**
Total Net Flux	**(7.4)**	**(9.0)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.8)**	**(8.8)**

Note: Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series. Parentheses indicate net sequestration.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 6-37: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (MMT C)

Soil Type	1990	2005	2009	2010	2011	2012	2013
Cropland Converted to Grassland							
Mineral	(1.7)	(2.5)	(2.4)	(2.4)	(2.4)	(2.4)	(2.3)
Organic	0.1	0.3	0.2	0.2	0.2	0.2	0.2
Forest Converted to Grassland							
Mineral	(0.3)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic	+	+	+	+	+	+	+
Other Lands Converted Grassland							
Mineral	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Organic	+	+	+	+	+	+	+
Settlements Converted Grassland							
Mineral	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)

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[46] CO_2 emissions associated with liming are also estimated but included in 6.4 Cropland Remaining Cropland.

Organic	+	+	+	+	+	+	+
Wetlands Converted Grassland							
Mineral	+	+	+	+	+	+	+
Organic	+	+	+	+	+	+	+
Total Mineral Soil Flux	**(2.2)**	**(2.8)**	**(2.7)**	**(2.7)**	**(2.7)**	**(2.7)**	**(2.7)**
Total Organic Soil Flux	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total Net Flux	**(2.0)**	**(2.5)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**

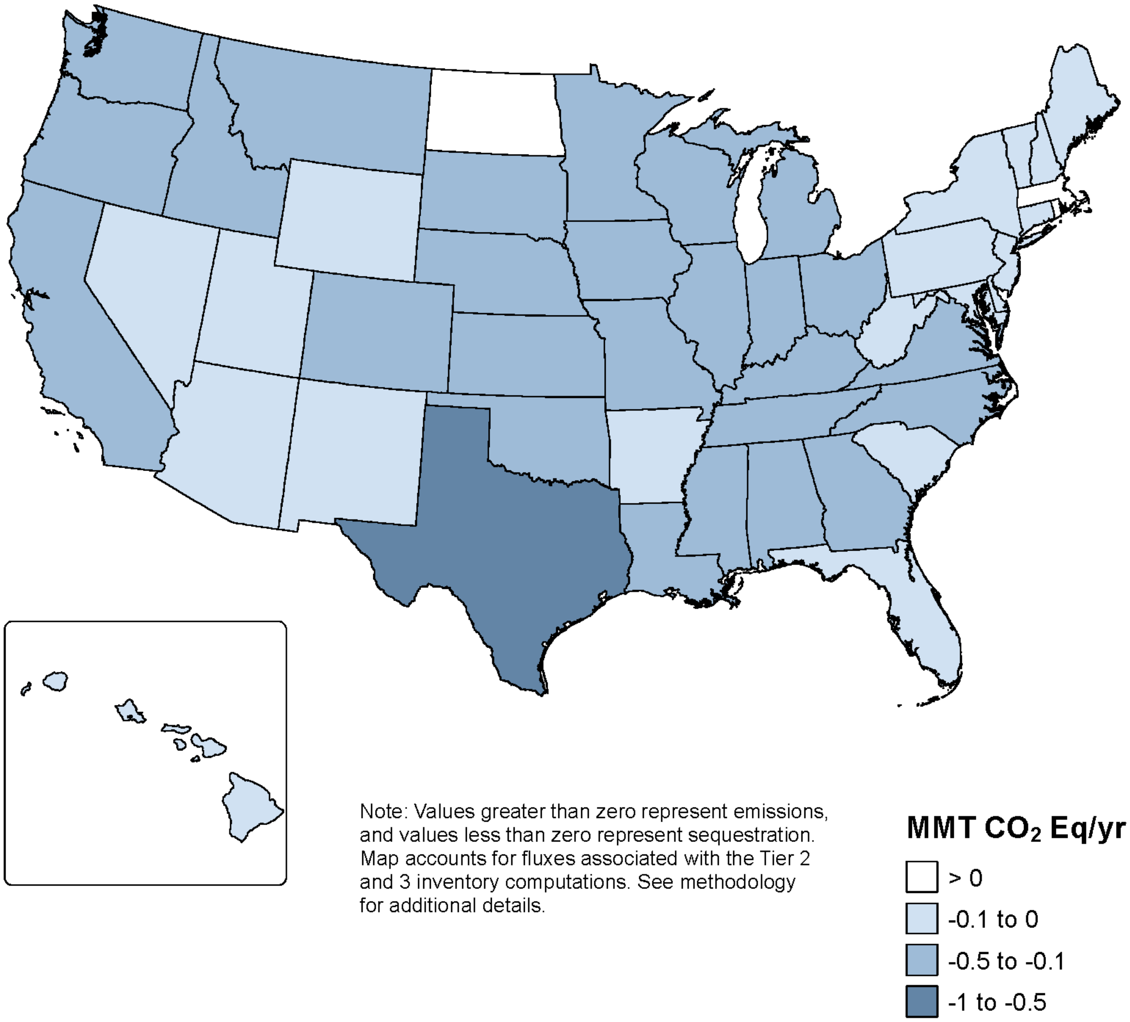
Note: Estimates after 2007 are based on NRI data from 2007 and therefore may not fully reflect changes occurring in the latter part of the time series.

Parentheses indicate net sequestration.

+ Does not exceed 0.05 MMT CO_2 Eq.

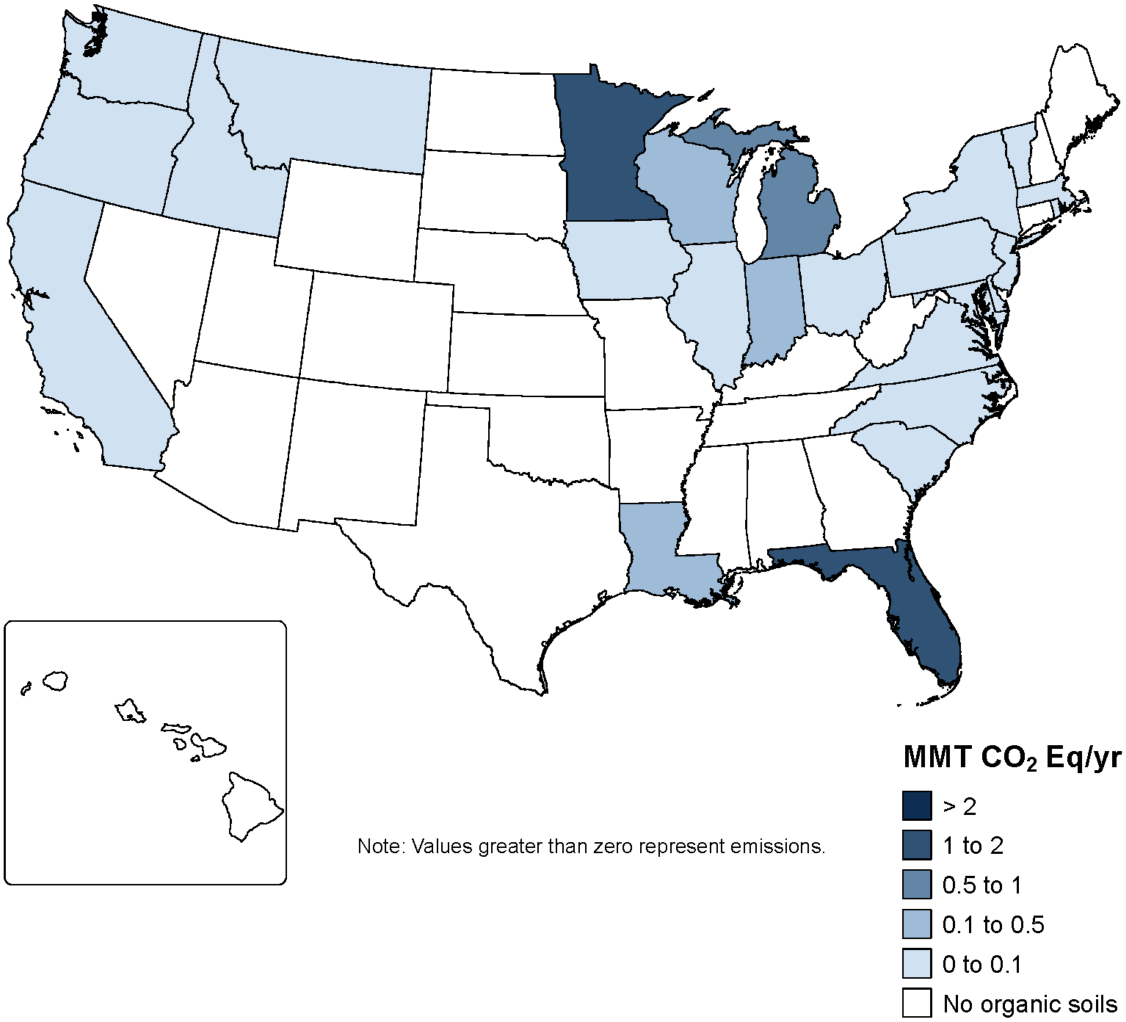
The spatial variability in the 2013 annual flux in CO_2 from mineral soils is displayed in Figure 6-14 and from organic soils in Figure 6-15. The soil C stock increased in most states for *Land Converted to Grassland*, which was driven by conversion of annual cropland into continuous pasture. The largest gains were in the Southeastern region, Northeast, South-Central, Midwest, and northern Great Plains. The regions with the highest rates of emissions from organic soils coincide with the largest concentrations of organic soils used for managed grasslands, including Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California).

Figure 6-14: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2013, *Land Converted to Grassland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See methodology for additional details.

Figure 6-15: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2013, *Land Converted to Grassland*



Note: Values greater than zero represent emissions.

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks for *Land Converted to Grassland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Biomass and litter C stock changes associated with conversion of forest to grassland are not explicitly included in this category, but are included in the *Forest Land Remaining Forest Land* section. Further elaboration on the methodologies and data used to estimate stock changes for mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil C stock changes were estimated for *Land Converted to Grassland* according to land-use histories recorded in the 2009 USDA NRI survey (USDA-NRCS 2009). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program initiated annual data collection, and the annual and data are currently available through 2010 (USDA-NRCS 2013). However, this Inventory only uses NRI data through 2007 because newer data were not made available in time to incorporate the additional years into this Inventory. NRI points were classified as *Land Converted to Grassland* in a given year between 1990 and 2007 if the land use was grassland but had been classified as another use during the previous 20 years.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) was applied to estimate C stock changes for *Land Converted to Grassland* on most mineral soils. C stock changes on the remaining soils were 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 from forest.[47]

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical[48] model (Parton et al. 1998; Del Grosso et al. 2001, 2011) as described for *Grassland Remaining Grassland*. The DAYCENT model utilizes the soil C 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 and management patterns were used in the DAYCENT simulations as recorded in the NRI survey (USDA-NCRS 2009), with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) and the National Agricultural Statistics Service (NASS 1992, 1999, 2004). See the *Cropland Remaining Cropland* section for additional discussion of the Tier 3 methodology for mineral soils.

Tier 2 Approach

For the mineral soils not included in the Tier 3 analysis, SOC stock changes were estimated using a Tier 2 Approach for *Land Converted to Grassland* as described in the Tier 2 portion of the *Cropland Remaining Cropland* section for mineral soils.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* were estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 6-38 for each subsource (i.e., mineral soil C stocks and organic soil C stocks), disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.12 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with 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 soil C stocks in *Land Converted to Grassland* ranged from 107 percent below to 107 percent above the 2013 stock change estimate of -8.8 MMT CO_2 Eq. The large relative uncertainty is due to the small net flux estimate in 2013.

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[47] Federal land is converted into private land in some cases due to changes in ownership. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2009), and so the land is assumed to be forest or nominal grassland for purposes of these calculations.

[48] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

Table 6-38: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (MMT CO_2 Eq. and Percent)

Source	2013 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 Grassland	**(7.7)**	**(17.1)**	**1.7**	**-122%**	**123%**
Mineral Soil C Stocks: Tier 3	(7.3)	(16.7)	2.0	-127%	127%
Mineral Soil C Stocks: Tier 2	(1.3)	(1.9)	(0.7)	-45%	45%
Organic Soil C Stocks: Tier 2	0.9	0.3	1.8	-63%	98%
Forests Converted to Grassland	**(0.3)**	**(0.6)**	**(0.1)**	**-62%**	**72%**
Mineral Soil C Stocks: Tier 2	(0.4)	(0.6)	(0.2)	-48%	44%
Organic Soil C Stocks: Tier 2	0.1	0.0	0.2	-100%	231%
Other Lands Converted to Grassland	**(0.2)**	**(0.3)**	**(0.1)**	**-48%**	**44%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	(0.1)	-48%	44%
Organic Soil C Stocks: Tier 2	NA	NA	NA	NA	NA
Settlements Converted to Grassland	**(0.5)**	**(0.7)**	**(0.3)**	**-51%**	**47%**
Mineral Soil C Stocks: Tier 2	(0.5)	(0.8)	(0.3)	-48%	44%
Organic Soil C Stocks: Tier 2	0.0	0.0	0.1	-86%	160%
Wetlands Converted to Grasslands	**(8.5)**	**(17.7)**	**0.7**	**-108%**	**108%**
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	(0.1)	-48%	44%
Organic Soil C Stocks: Tier 2	0.1	0.0	0.2	-58%	81%
Total: Land Converted to Grassland	**(8.8)**	**(18.1)**	**0.7**	**-107%**	**107%**
Mineral Soil C Stocks: Tier 3	**(7.3)**	**(16.7)**	**2.0**	**-127%**	**127%**
Mineral Soil C Stocks: Tier 2	**(2.5)**	**(3.2)**	**(1.9)**	**-27%**	**26%**
Organic Soil C Stocks: Tier 2	**1.1**	**0.5**	**2.0**	**-52%**	**81%**

Note: Parentheses indicate negative values.

NA: Other land by definition does not include organic soil (see Section 6.1— of the U.S. Land Base). Consequently, no land areas, C stock changes, or uncertainty results are estimated for land use conversions from Other lands to Croplands and Other lands to Grasslands on organic soils.

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of agricultural biomass and litter C stock changes, other than the loss of forest biomass and litter, which is reported in the *Forest Land Remaining Forest Land* section of the report. Biomass C stock changes may be significant for managed grasslands with woody encroachment that has not attained enough tree cover to be considered forest lands. Changes in litter C stocks are assumed to be negligible in grasslands over annual time frames, although there are likely significant changes at sub-annual time scales across seasons.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the above Methodology section.

QA/QC and Verification

See the QA/QC and Verification section in *Grassland Remaining Grassland*.

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements: 1) refining parameters associated with simulating crop production and carbon inputs to the soil in the DAYCENT biogeochemical model; 2) improving the model simulation of snow melt and water infiltration in soils; and 3) driving the DAYCENT simulations with updated input data for the excretion of C and nitrogen (N) onto Pasture/Range/Paddock and N additions from managed manure based on national livestock population. As a result of these improvements to the Inventory, changes in SOC stocks increased by an average of 0.2 MMT CO_2 eq. annually over the time series.

Planned Improvements

Soil C stock changes with land use conversion from forest land to grassland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and grasslands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to grassland. This planned improvement may not be fully implemented for two more years, depending on resource availability. Another key planned improvement for the *Land Converted to Grassland* category is to develop an inventory of carbon stock changes for the 800,000 to 850,000 hectares of Federal grasslands in the western United States. Grasslands in Alaska will also be evaluated. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland*.

6.8 Wetlands Remaining Wetlands (IPCC Source Category 4D1)

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands which 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, or conversion of the land to another use.

CO_2 emissions from the removal of biomass and the decay of drained peat constitute the major GHG 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 shut down 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. CH_4 emissions were considered insignificant under 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). N_2O emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release GHG emissions, and at present no methodology is provided by IPCC (2006) to estimate greenhouse gas emissions or removals from restored peatlands; although methodologies are provided for rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines. This Inventory estimates CO_2, N_2O, and CH_4 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 methodologies estimate only on-site N_2O and CH_4 emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat, and off-site CH_4 emissions are not relevant given the non-energy uses of peat, so methodologies are not provided in IPCC (2013) guidelines. On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some 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 located on highly fertile soils contain significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O, and contributes to the activity of methanogens and methanotrophs (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed as land is drained 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 carbon losses and the horticultural and landscaping use of peat. As drainage waters in peatlands accumulate, dissolved organic carbon reacts within aquatic ecosystems and is converted to CO_2, 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 98 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* were estimated to be 0.8 MMT CO_2 Eq. in 2013 (see Table 6-39) comprising 0.8 MMT CO_2 Eq. (770 kt) of CO_2, 0.001 MMT CO_2 Eq. (0.002 kt) of N_2O, and 0.004 MMT CO_2 Eq. (0.16 kt) of CH_4. Total emissions in 2013 were about 5 percent smaller than total emissions in 2012. Peat production in Alaska in 2013 was not reported in *Alaska's Mineral Industry 2013* report. However, peat production reported in the lower 48 states in 2013 was 5 percent lower than in 2012, resulting in smaller total 48 states plus Alaska emissions from *Peatlands Remaining Peatlands* in 2013 compared to 2012.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.8 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993 followed by an increasing trend through 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009, when the trend reversed. Emissions in 2013 represent a decline from emissions in 2012. CO_2 emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.8 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. CH_4 and N_2O emissions remained close to zero across the time series. N_2O emissions showed a decreasing trend from 1990 until 1995, followed by an increasing trend through 2001. N_2O emissions decreased between 2001 and 2006, followed by a leveling off between 2008 and 2010, and a decline between 2011 and 2013. CH_4 emissions decreased from 1990 until 1995, followed by an increasing trend through 2000, a period of fluctuation through 2010, then a decline between 2011 and 2013.

Table 6-39: Emissions from *Peatlands Remaining Peatlands* (MMT CO_2 Eq.)

Gas	1990		2005		2009	2010	2011	2012	2013
CO_2	1.1		1.1		1.0	1.0	0.9	0.8	0.8
Off-site	1.0		1.0		1.0	1.0	0.9	0.8	0.7
On-site	0.1		0.1		0.1	0.1	0.1	0.1	+
N_2O (On-site)	+		+		+	+	+	+	+
CH_4 (On-site)	+		+		+	+	+	+	+
Total	**1.1**		**1.1**		**1.0**	**1.0**	**0.9**	**0.8**	**0.8**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
+ Less than 0.05 MMT CO_2 Eq.
Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Guidance for estimating off-site CH_4 emissions is not included in IPCC (2013). Totals may not sum due to independent rounding.

Table 6-40: Emissions from *Peatlands Remaining Peatlands* (kt)

Gas	1990	2005	2009	2010	2011	2012	2013
CO_2	1,055	1,101	1,024	1,022	926	812	770
Off-site	985	1,030	957	956	866	760	720
On-site	70	71	67	66	60	53	50
N_2O (On-site)	+	+	+	+	+	+	+
CH_4 (On-site)	+	+	+	+	+	+	+

+ Less than 0.5 kt

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Guidance for estimating off-site CH_4 emissions is not included in IPCC (2013). Totals may not sum due to independent rounding.

Methodology

Off-site CO_2 Emissions

CO_2 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 6-41) 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 lower 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 1995–2014a; USGS 2014b). To develop these data, the U.S. Geological Survey (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; and USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993–2014). 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 lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates Alaska emissions separately from lower 48 emissions because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 6-42). 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).[49] Peat production was not reported for 2013 in *Alaska's Mineral Industry 2013* report (DGGS 2014); therefore Alaska's peat production in 2013 (reported in cubic yards) was assumed to be equal to its peat production in 2012.

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. CO_2 emissions from dissolved organic C were

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[49] 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).

estimated by multiplying the area of peatlands by the default emissions factor for dissolved organic C provided in IPCC (2013).

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over two-and-a-half times the amount of domestic peat production. However, consistent with the Tier 1 method whereby only domestic peat production is accounted for when estimating off-site emissions, off-site CO_2 emissions from the use of peat not produced within the United States are not included in the Inventory. The United States has largely imported peat from Canada for horticultural purposes; from 2010 to 2013, imports of sphagnum moss (nutrient-poor) peat from Canada represented 63 percent of total U.S. peat imports (USGS 2015). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient rich by IPCC (2006). 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.

Table 6-41: Peat Production of Lower 48 States (kt)

Type of Deposit	1990	2005	2009	2010	2011	2012	2013
Nutrient-Rich	595.1	657.6	560.3	558.9	511.2	409.9	418.5
Nutrient-Poor	55.4	27.4	48.7	69.1	56.8	78.1	46.5
Total Production	**692.0**	**685.0**	**609.0**	**628.0**	**568.0**	**488.0**	**465.0**

Sources: United States Geological Survey (USGS) (1991–2014a) *Minerals Yearbook: Peat (1994–2013);* United States Geological Survey (USGS) (2014b) *Mineral Commodity Summaries: Peat (2013).*

Table 6-42: Peat Production of Alaska (Thousand Cubic Meters)

	1990	2005	2009	2010	2011	2012	2013
Total Production	49.7	47.8	183.9	59.8	61.5	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2014) *Alaska's Mineral Industry Report (1997–2013).*

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 in accordance with IPCC (2006), an average production rate for the industry was applied to derive an 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).[50] The area of land managed for peat extraction in the United States was estimated using 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. 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 same assumption that a single hectare yields 100 metric tons. The IPCC (2006) on-site emissions equation also includes a term which accounts for emissions resulting from the change in C 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

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[50] 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).

extraction. Other changes in C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emission estimates on the area of 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 area data from production data. In order to estimate N_2O emissions, the area of nutrient rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2013).

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 area 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).

Uncertainty and Time-Series Consistency

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 the 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 lower 48 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). Based on these values and distributions, 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*. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-43. CO_2 emissions from *Peatlands Remaining Peatlands* in 2013 were estimated to be between 0.5 and 1.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 29 percent below to 32 percent above the 2013 emission estimate of 0.8 MMT CO_2 Eq. N_2O emissions from *Peatlands Remaining Peatlands* in 2013 were estimated to be between 0.0003 and 0.0010 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 55 percent below to 62 percent above the 2013 emission estimate of 0.0006 MMT CO_2 Eq. CH_4 emissions from *Peatlands Remaining Peatlands* in 2013 were estimated to be between 0.002 and 0.007 MMT CO_2 Eq. This indicates a range of 60 percent below to 85 percent above the 2013 emission estimate of 0.004 MMT CO_2 Eq.

Table 6-43: 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	2013 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**
Peatlands Remaining Peatlands	CO_2	0.8	0.5	1.0	−29%	32%
Peatlands Remaining Peatlands	CH_4	+	+	+	−60%	85%
Peatlands Remaining Peatlands	N_2O	+	+	+	−55%	62%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

+ Does not exceed 0.05 MMT CO_2 eq.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis revealed an incorrect emission factor for off-site CO_2 emissions from dissolved organic carbon. The emission factor for a boreal climate zone was replaced with the emission factor for a temperate climate zone, which is more representative of the climate zone for the majority of peat producing areas in the United States.

The QA/QC analysis also revealed that revised production estimates for peat were published in the *2013 Minerals Yearbook: Peat* (USGS 2014a). The estimates for the U.S. production of peat and the percentage of sphagnum moss (nutrient-poor peat) reported in the *2013 Mineral Commodity Summaries: Peat* (USGS 2014b) were replaced with the estimates reported in the *2013 Minerals Yearbook: Peat* (USGS 2014a). As a result, the estimate for peat production decreased by 3 percent and the percentage of sphagnum moss decreased by 6 percent.

Recalculations Discussion

The emissions estimates for *Peatlands Remaining Peatlands* were updated to reflect the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). IPCC (2013) methodologies include off-site CO_2 emissions from dissolved organic carbon, on-site CH_4 emissions from drainage ditches and drained land surface, and updated emissions factors for off-site CO_2, on-site CO_2, and on-site N_2O emissions estimates. As a result of the methodological changes listed above, CO_2 emissions over the entire time series increased by an average of approximately 1 percent and N_2O emissions over the entire time series decreased by an average of approximately 500 percent. Total emissions from *Peatlands Remaining Peatlands* increased by an average of approximately 1 percent over the entire time series relative to the previous emissions estimates using the IPCC (2006) guidelines.

The current Inventory estimates for 2011 and 2012 were also updated to incorporate information on the volume of peat production in Alaska from *Alaska's Mineral Industry 2012* report (DGGS 2013); and the historical estimate for 2004 was updated to incorporate more recent information on the volume of peat product in Alaska in 2004 from *Alaska's Mineral Industry 2006* report (DGGS 2007). In the previous Inventory report, peat production in Alaska in 2011 and 2012 was assumed to equal the values reported for 2011 and 2012 in the *2012 Minerals Yearbook: Peat* (USGS 2013). As a result of the updated production estimates, emissions decreased by 0.005 percent in 2011, increased by 0.001 percent in 2012, and increased by 10 percent in 2004. Since no peat production was reported in *Alaska's Mineral Industry 2013* report, peat production in Alaska in 2013 was assumed to equal the value reported for 2012 in *Alaska's Mineral Industry 2012* report; this will result in a recalculation in the next Inventory report if the production value is updated.

In addition, for the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWP of CH_4 has increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWP of N_2O has decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter. As a result of the updated GWP value for N_2O, N_2O emissions estimates for each year from 1990 to 2012 decreased by 4 percent relative to the N_2O emissions estimates in previous Inventory reports.

Planned Improvements

In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from *Peatlands Remaining Peatlands*, future efforts will consider options for obtaining better data on the quantity of peat harvested per hectare and the total area undergoing peat extraction.

6.9 Settlements Remaining Settlements

Changes in Carbon Stocks in Urban Trees (IPCC Source Category 4E1)

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). Urban areas (cities, towns, and villages) are estimated to cover over 3 percent of the United States (U.S. Census Bureau 2012). With an average tree canopy cover of 35 percent, urban areas account for approximately 5 percent of total tree cover in the continental United States (Nowak and Greenfield 2012). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 75.8 MMT CO_2 Eq. (20.7 MMT C) over the period from 1990 through 2013. Net C flux from urban trees in 2013 was estimated to be −89.5 MMT CO_2 Eq. (−24.4 MMT C). Annual estimates of CO_2 flux (Table 6-44) were developed based on periodic (1990, 2000, and 2010) U.S. Census data on urbanized area. The estimate of urbanized area is smaller than the area categorized as *Settlements* in the Representation of the U.S. Land Base developed for this report, by an average of 48 percent over the 1990 through 2013 time series—i.e., the Census urban area is a subset of the *Settlements* area.

In 2013, urban area was about 44 percent smaller than the total area defined as *Settlements.* Census area data are preferentially used to develop C flux estimates for this source category since these data are more applicable for use with the available peer-reviewed data on urban tree canopy cover and urban tree C sequestration. Annual sequestration increased by 48 percent between 1990 and 2013 due to increases in urban land area. Data on C storage and urban tree coverage were collected since the early 1990s and have been applied to the entire time series in this report. As a result, the estimates presented in this chapter are not truly representative of changes in C stocks in urban trees for *Settlements* areas, but are representative of changes in C stocks in urban trees for Census urban area. The method used in this report does not attempt to scale these estimates to the *Settlements* area. Therefore, the estimates presented in this chapter are likely an underestimate of the true changes in C stocks in urban trees in all *Settlements* areas—i.e., the changes in C stocks in urban trees presented in this chapter are a subset of the changes in C stocks in urban trees in all *Settlements* areas.

Urban trees often grow faster than forest trees because of the relatively open structure of the urban forest (Nowak and Crane 2002). However, areas in each case are accounted for differently. Because urban areas contain less tree coverage than forest areas, the C storage per hectare of land is in fact smaller for urban areas. However, urban tree reporting occurs on a basis of C sequestered per unit area of tree cover, rather than C sequestered per total land area. Expressed per unit of tree cover, areas covered by urban trees have a greater C density than do forested areas (Nowak and Crane 2002). Expressed per unit of land area, however, the situation is the opposite: Urban areas have a smaller C density than forest areas.

Table 6-44: Net C Flux from Urban Trees (MMT CO_2 Eq. and MMT C)

Year	MMT CO_2 Eq.	MMT C
1990	(60.4)	(16.5)
2005	(80.5)	(22.0)
2009	(85.0)	(23.2)
2010	(86.1)	(23.5)

2011	(87.3)	(23.8)
2012	(88.4)	(24.1)
2013	(89.5)	(24.4)

Note: Parentheses indicate net sequestration.

Methodology

Methods for quantifying urban tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, the methodology used by Nowak et al. (2013) to estimate net C sequestration in urban trees followed three steps. First, field data from cities and states were used to generate allometric estimates of biomass from measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, land-use class, and growing season to generate estimates of gross C sequestration in urban trees for all 50 states and the District of Columbia. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration values to derive estimates of net C sequestration. Finally, sequestration estimates for all 50 states and the District of Columbia, in units of C sequestered per unit area of tree cover, were used to estimate urban forest C sequestration in the United States by using urban area estimates from U.S. Census data and urban tree cover percentage estimates for each state and the District of Columbia from remote sensing data, an approach consistent with Nowak et al. (2013).

This approach is also consistent with the default IPCC methodology in IPCC (2006), although sufficient data are not yet available to separately determine interannual gains and losses in C stocks in the living biomass of urban trees.

In order to generate the allometric relationships between tree dimensions and tree biomass for cities and states, Nowak et al. (2013) and previously published research (Nowak and Crane 2002; and Nowak 1994, 2007b, and 2009) collected field measurements in a number of U.S. cities between 1989 and 2012. For a sample of trees in each of the cities in Table 6-45, data including tree measurements of stem diameter, tree height, crown height and crown width, and information on location, species, and canopy condition were collected. The data for each tree were converted into C storage by applying allometric equations to estimate aboveground biomass, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, moisture content, a C content of 50 percent (dry weight basis), and an adjustment factor of 0.8 to account for urban trees having less aboveground biomass for a given stem diameter than predicted by allometric equations based on forest trees (Nowak 1994). C storage estimates for deciduous trees include only C stored in wood. These calculations were then used to develop an allometric equation relating tree dimensions to C storage for each species of tree, encompassing a range of diameters.

Tree growth was estimated using annual height growth and diameter growth rates for specific land uses and diameter classes. Growth calculations were adjusted by a factor to account for tree condition (fair to excellent, poor, critical, dying, or dead). For each tree, the difference in C storage estimates between year 1 and year (x + 1) represents the gross amount of C sequestered. These annual gross C sequestration rates for each species (or genus), diameter class, and land-use condition (e.g., parks, transportation, vacant, golf courses) were then scaled up to city estimates using tree population information. 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 (Nowak 2011).

Most of the field data used to develop the methodology of Nowak et al. (2013) were analyzed using the U.S. Forest Service's Urban Forest Effects (UFORE) model. UFORE is a computer model that uses standardized field data from random plots in each city and local air pollution and meteorological data to quantify urban forest structure, values of the urban forest, and environmental effects, including total C stored and annual C sequestration. UFORE was used with field data from a stratified random sample of plots in each city to quantify the characteristics of the urban forest (Nowak et al. 2007).

Where gross C sequestration accounts for all carbon sequestered, net C sequestration takes into account carbon emissions associated with urban trees. Net C emissions include tree death and removals. Estimates of net C emissions from urban trees were derived by applying estimates of annual mortality and condition, and assumptions about whether dead trees were removed from the site to the total C stock estimate for each city. Estimates of annual mortality rates by diameter class and condition class were derived 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. The estimated annual gross C emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information.

The data for all 50 states and the District of Columbia are described in Nowak et al. (2013), which builds upon previous research, including: Nowak and Crane (2002), Nowak et al. (2007), and references cited therein. The allometric equations applied to the field data for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric equation could be found for the particular species, the average result for the genus was used. The adjustment (0.8) to account for less live tree biomass in 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 (BG) 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 health and 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 6-45) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state urban area and urban tree cover data to calculate each state's annual net C sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified to incorporate U.S. Census data.

Specifically, urban area estimates were based on 1990, 2000, and 2010 U.S. Census data. The 1990 U.S. Census defined urban land as "urbanized areas," which included land with a population density greater than 1,000 people per square mile, and adjacent "urban places," which had predefined political boundaries and a population total greater than 2,500. In 2000, the U.S. Census replaced the "urban places" category with a new category of urban land called an "urban cluster," which included areas with more than 500 people per square mile. In 2010, the Census updated its definitions to have "urban areas" encompassing Census tract delineated cities with 50,000 or more people, and "urban clusters" containing Census tract delineated locations with between 2,500 and 50,000 people. Urban land area increased by approximately 23 percent from 1990 to 2000 and 14 percent from 2000 to 2010; Nowak et al. (2005) estimate that the changes in the definition of urban land are responsible for approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under all Census (i.e., 1990, 2000, and 2010) definitions, the urban category encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). *Settlements* area, as assessed in the Representation of the U.S. Land Base developed for this report, encompassed all developed parcels greater than 0.1 hectares in size, including rural transportation corridors, and as previously mentioned represents a larger area than the Census-derived urban area estimates. However, the smaller, Census-derived urban area estimates were deemed to be more suitable for estimating national urban tree cover given the data available in the peer-reviewed literature (i.e., the data set available is consistent with Census urban rather than *Settlements* areas), and the recognized overlap in the changes in C stocks between urban forest and non-urban forest (see Planned Improvements below). U.S. Census urban area data is reported as a series of continuous blocks of urban area in each state. The blocks or urban area were summed to create each state's urban area estimate.

Net annual C sequestration estimates were derived for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.74, the standard ratio for net/gross sequestration set out in Table 3 of Nowak et al. (2013) (unless data existed for both gross and net sequestration for the state in Table 2 of Nowak et. al. (2013), in which case they were divided to get a state-specific ratio). The gross and net annual C sequestration values for each state were multiplied by each state's area of tree cover, which was the product of the state's urban/community area as defined in the U.S. Census (2012) and the state's urban/community tree cover percentage. The urban/community tree cover percentage estimates for all 50 states were obtained from Nowak and Greenfield (2012), which compiled ten years of research including Dwyer et al. (2000), Nowak et al. (2002), Nowak (2007a), and Nowak (2009). The urban/community tree cover percentage estimate for the District of Columbia was obtained from Nowak et al.

(2013). The urban area estimates were taken from the 2010 U.S. Census (2012). The equation, used to calculate the summed carbon sequestration amounts, can be written as follows:

$$\text{Net annual C sequestration} = \text{Gross sequestration rate} \times \text{Net to Gross sequestration ratio} \times \text{Urban Area} \times \text{\% Tree Cover}$$

Table 6-45: Annual C Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m^2-yr) for 50 states plus the District of Columbia

State	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net: Gross Annual Sequestration Ratio
Alabama	1,123,944	831,718	55.2	0.343	0.254	0.74
Alaska	44,895	33,223	39.8	0.168	0.124	0.74
Arizona	369,243	273,239	17.6	0.354	0.262	0.74
Arkansas	411,363	304,409	42.3	0.331	0.245	0.74
California	2,092,278	1,548,286	25.1	0.389	0.288	0.74
Colorado	149,005	110,264	18.5	0.197	0.146	0.74
Connecticut	766,512	567,219	67.4	0.239	0.177	0.74
Delaware	129,813	96,062	35.0	0.335	0.248	0.74
DC	14,557	11,568	35.0	0.263	0.209	0.79
Florida	3,331,471	2,465,288	35.5	0.475	0.352	0.74
Georgia	2,476,627	1,832,704	54.1	0.353	0.261	0.74
Hawaii	241,105	178,417	39.9	0.581	0.430	0.74
Idaho	24,658	18,247	10.0	0.184	0.136	0.74
Illinois	747,411	553,084	25.4	0.283	0.209	0.74
Indiana	396,776	366,882	23.7	0.250	0.231	0.92
Iowa	115,796	85,689	19.0	0.240	0.178	0.74
Kansas	182,154	141,747	25.0	0.283	0.220	0.78
Kentucky	237,287	175,592	22.1	0.286	0.212	0.74
Louisiana	727,949	538,683	34.9	0.397	0.294	0.74
Maine	107,875	79,827	52.3	0.221	0.164	0.74
Maryland	586,554	434,050	34.3	0.323	0.239	0.74
Massachusetts	1,294,359	957,826	65.1	0.254	0.188	0.74
Michigan	731,314	541,172	35.0	0.220	0.163	0.74
Minnesota	349,007	258,265	34.0	0.229	0.169	0.74
Mississippi	480,298	355,421	47.3	0.344	0.255	0.74
Missouri	488,287	361,332	31.5	0.285	0.211	0.74
Montana	52,675	38,980	36.3	0.184	0.136	0.74
Nebraska	49,685	41,927	15.0	0.238	0.201	0.84
Nevada	41,797	30,929	9.6	0.207	0.153	0.74
New Hampshire	244,715	181,089	66.0	0.217	0.161	0.74
New Jersey	1,192,996	882,817	53.3	0.294	0.218	0.74
New Mexico	68,789	50,904	12.0	0.263	0.195	0.74
New York	1,090,092	806,668	42.6	0.240	0.178	0.74
North Carolina	1,989,946	1,472,560	51.1	0.312	0.231	0.74
North Dakota	14,372	6,829	13.0	0.223	0.106	0.48
Ohio	910,839	674,021	31.5	0.248	0.184	0.74
Oklahoma	358,363	265,189	31.2	0.332	0.246	0.74
Oregon	257,480	190,535	36.6	0.242	0.179	0.74
Pennsylvania	1,241,922	919,022	41.0	0.244	0.181	0.74
Rhode Island	136,841	101,262	51.0	0.258	0.191	0.74
South Carolina	1,063,705	787,141	48.9	0.338	0.250	0.74
South Dakota	20,356	17,653	14.0	0.236	0.205	0.87
Tennessee	1,030,972	921,810	43.8	0.303	0.271	0.89
Texas	2,712,954	2,007,586	31.4	0.368	0.272	0.74
Utah	87,623	64,841	16.4	0.215	0.159	0.74
Vermont	46,111	34,122	53.0	0.213	0.158	0.74
Virginia	822,286	608,492	39.8	0.293	0.217	0.74
Washington	560,055	414,440	34.6	0.258	0.191	0.74
West Virginia	249,592	184,698	61.0	0.241	0.178	0.74

Wisconsin	356,405	263,739	31.8	0.225	0.167	0.74
Wyoming	18,726	13,857	19.9	0.182	0.135	0.74

Uncertainty and Time-Series Consistency

Uncertainty associated with changes in C stocks in urban trees includes the uncertainty associated with urban area, percent urban tree coverage, and estimates of gross and net C sequestration for each of the 50 states and the District of Columbia. A 10 percent uncertainty was associated with urban area estimates based on expert judgment. Uncertainty associated with estimates of percent urban tree coverage for each of the 50 states was based on standard error estimates reported by Nowak and Greenfield (2012). Uncertainty associated with estimate of percent urban tree coverage for the District of Columbia was based on the standard error estimate reported by Nowak et al. (2013). Uncertainty associated with estimates of gross and net C 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 reported by Nowak et al. (2013). 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 equations, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there may be some overlap between the urban tree C estimates and the forest tree C estimates. Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of urban 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. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-46. The net C flux from changes in C stocks in urban trees in 2013 was estimated to be between −133.1 and −47.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 49 percent more sequestration to 48 percent less sequestration than the 2013 flux estimate of −89.5 MMT CO_2 Eq.

Table 6-46: Approach 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Changes in C Stocks in Urban Trees	CO_2	(89.5)	(133.1)	(47.0)	49%	−48%

Note: Parentheses indicate negative values or net sequestration.

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

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 urban 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. The net C flux resulting from urban trees was predominately calculated using state-specific estimates of gross and net C sequestration estimates for urban trees and urban tree coverage area published in the literature.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed at the beginning of the *Land Use, Land-Use Change, and Forestry* chapter, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between urban forest and non-urban forest greenhouse gas inventories. Urban forest inventories are including areas also defined as forest land under the Forest Inventory and Analysis (FIA) program of the USDA Forest Service, resulting in "double-counting" of these land areas in estimates of C stocks and fluxes for this report. For example, Nowak et al. (2013) estimates that 13.7 percent of urban land is measured by the forest inventory plots, and could be responsible for up to 87 MMT C of overlap.

Future research may also enable more complete coverage of changes in the C stock in urban trees for all *Settlements* land. To provide estimates for all *Settlements*, research would need to establish the extent of overlap between *Settlements* and Census-defined urban areas, and would have to characterize sequestration on non-urban *Settlements* land.

N_2O Fluxes from Settlement Soils (IPCC Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 2.4 percent are currently applied to lawns, golf courses, and other landscaping occurring within settlement areas. Application rates are lower than those occurring on cropped soils, and, therefore, account for a smaller proportion of total U.S. soil N_2O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface applied sewage sludge is applied to settlement areas.

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 and sludge N that is transformed and transported to another location in a form other than N_2O (NH_3 and NO_x volatilization, NO_3 leaching and runoff), 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.

In 2013, total N_2O emissions from settlement soils were 2.4 MMT CO_2 Eq. (8 kt). There was an overall increase of 77 percent over the period from 1990 through 2013 due to a general increase in the application of synthetic N fertilizers on an expanding settlement area. Interannual variability in these emissions is directly attributable to interannual variability in total synthetic fertilizer consumption and sewage sludge applications in the United States. Emissions from this source are summarized in Table 6-47.

Table 6-47: N_2O Fluxes from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and kt N_2O)

	1990		2005		2009	2010	2011	2012	2013
Direct N_2O Fluxes from Soils									
MMT CO_2 Eq.	1.0		1.8		1.7	1.8	1.9	1.9	1.8
kt N_2O	3		6		6	6	6	6	6
Indirect N_2O Fluxes from Soils									
MMT CO_2 Eq.	0.4		0.6		0.6	0.6	0.6	0.6	0.6
kt N_2O	1		2		2	2	2	2	2
Total									
MMT CO_2 Eq.	**1.4**		**2.3**		**2.2**	**2.4**	**2.5**	**2.5**	**2.4**
kt N_2O	**5**		**8**		**8**	**8**	**8**	**8**	**8**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Methodology

For soils within *Settlements Remaining Settlements*, the IPCC Tier 1 approach was used to estimate soil N_2O emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N_2O emissions from soils in settlements were based on the amount of N in synthetic commercial fertilizers applied to settlement soils, and the amount of N in sewage sludge applied to non-agricultural land and surface disposal (see Annex 3.12 for a detailed discussion of the methodology for estimating sewage sludge application).

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Ruddy et al. 2006). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1982 through 2001 (Ruddy et al. 2006). Non-farm N fertilizer was assumed to be applied to settlements and forest lands; values for 2002 through 2013 were based on 2001 values adjusted for annual total N fertilizer sales in the United States because there is no new activity data on application after 2001. Settlement application was calculated by subtracting forest application from total non-farm fertilizer use. Sewage sludge applications were derived from national data on sewage sludge generation, disposition, and N content (see Annex 3.12 for further detail). The total amount of N resulting from these sources was multiplied by the IPCC default emission factor for applied N (1 percent) to estimate direct N_2O emissions (IPCC 2006).

For indirect emissions, the total N applied from fertilizer and sludge was 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 was multiplied by the IPCC default factor of 1 percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff was 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 were summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from settlements depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, 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 flux is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variations in fertilizer N and sewage sludge application rates. All settlement soils are treated equivalently under this methodology.

Uncertainties exist in both the fertilizer N and sewage sludge application rates in addition to the emission factors. Uncertainty in fertilizer N application was assigned a default level of ±50 percent.[51] Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was derived from variability in several factors, including: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal. The uncertainty ranges around 2005 activity data and emission factor input variables were directly applied to the 2013 emission estimates. Uncertainty in the direct and indirect emission factors was provided by the IPCC (2006).

Quantitative uncertainty of this source category was estimated using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-48. Direct N_2O emissions from soils in *Settlements Remaining Settlements* in 2013 were estimated to be between 0.9 and 4.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2013 emission estimate of 1.8 MMT CO_2 Eq. Indirect N_2O emissions in 2013 were between 0.1 and 1.9 MMT CO_2 Eq., ranging from a -85 percent to 212 percent around the estimate of 0.6 MMT CO_2 Eq.

Table 6-48: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
Settlements Remaining Settlements:			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	1.8	0.9	4.8	-49%	163%
Indirect N_2O Fluxes from Soils	N_2O	0.6	0.1	1.9	-85%	212%

Note: These estimates include direct and indirect N_2O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

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[51] No uncertainty is provided with the USGS fertilizer consumption data (Ruddy et al. 2006) so a conservative ±50 percent was used in the analysis.

QA/QC and Verification

The spreadsheet containing fertilizer and sewage sludge applied to settlements and calculations for N_2O and uncertainty ranges were checked and corrections were made. Linkage errors in the uncertainty calculation for 2013 were found and corrected. The reported emissions in the Inventory were also adjusted accordingly.

Recalculations Discussion

Indirect emissions from settlements were previously reported in *Agricultural Soil Management*, but are now included in this source category. Including indirect emissions resulted in a 66 percent increase.

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous Inventories) which results in time-series recalculations for most Inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWP of N_2O decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Planned Improvements

A minor improvement is planned to update the uncertainty analysis for direct emissions from settlements to be consistent with the most recent activity data for this source.

6.10 Land Converted to Settlements (IPCC Source Category 4E2)

Land-use change is constantly occurring, and land under a number of uses undergoes urbanization in the United States each year. However, data on the amount of land converted to settlements is currently lacking. Given the lack of available information relevant to this particular IPCC source category, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Settlements* from fluxes on *Settlements Remaining Settlements* at this time.

6.11 Other (IPCC Source Category 4H)

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

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 discarded in landfills. Carbon (C) contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon-storage estimates are associated with particular land uses. For example, harvested wood products are accounted for under *Forest Land Remaining Forest Land* because these wood products are considered a component of the forest ecosystem. The wood products serve as reservoirs to which C resulting from photosynthesis in trees is transferred, but the removals in this case occur in the forest. Carbon stock changes in yard trimmings and food scraps are associated with settlements, but removals in this case do not occur within settlements. To address this complexity, yard trimming and food scrap C storage is reported under the “Other” source category.

Both the amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2014a). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 3 percent decrease in the tonnage of yard trimmings generated (i.e., collected for composting or disposal). 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—from 72 percent in 1990 to 35 percent in 2013. The net effect of the reduction in generation and the increase in composting is a 53 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.

Food scrap generation has grown by 53 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 78 percent in 2013, the tonnage disposed of in landfills has increased considerably (by 46 percent). 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 annual landfill C storage from 26.0 MMT CO_2 Eq. (7.1 MMT C) in 1990 to 12.6 MMT CO_2 Eq. (3.4 MMT C) in 2013 (Table 6-49 and Table 6-50).

Table 6-49: Net Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
Yard Trimmings	(21.0)	(7.4)	(8.5)	(9.3)	(9.4)	(9.3)	(9.3)
Grass	(1.8)	(0.6)	(0.8)	(0.9)	(0.9)	(0.9)	(0.9)
Leaves	(9.0)	(3.4)	(3.9)	(4.2)	(4.3)	(4.3)	(4.3)
Branches	(10.2)	(3.4)	(3.8)	(4.1)	(4.2)	(4.2)	(4.2)
Food Scraps	(5.0)	(4.0)	(4.0)	(3.9)	(3.8)	(3.4)	(3.3)
Total Net Flux	**(26.0)**	**(11.4)**	**(12.5)**	**(13.2)**	**(13.2)**	**(12.8)**	**(12.6)**

Note: Parentheses indicate net sequestration.

Table 6-50: Net Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	**1990**	**2005**	**2009**	**2010**	**2011**	**2012**	**2013**
Yard Trimmings	**(5.7)**	**(2.0)**	**(2.3)**	**(2.5)**	**(2.6)**	**(2.5)**	**(2.5)**
Grass	(0.5)	(0.2)	(0.2)	(0.3)	(0.3)	(0.2)	(0.2)
Leaves	(2.5)	(0.9)	(1.1)	(1.1)	(1.2)	(1.2)	(1.2)
Branches	(2.8)	(0.9)	(1.0)	(1.1)	(1.1)	(1.1)	(1.1)
Food Scraps	**(1.4)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.0)**	**(0.9)**	**(0.9)**
Total Net Flux	**(7.1)**	**(3.1)**	**(3.4)**	**(3.6)**	**(3.6)**	**(3.5)**	**(3.4)**

Note: Parentheses indicate net sequestration.

Methodology

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the global C 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 C in landfills can increase, with the net effect being a net atmospheric removal of C. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years, based on methodologies presented for the *Land Use, Land-Use Change, and Forestry* sector in IPCC (2003). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings or food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the mass of C that was landfilled in previous years that decomposed.

To determine the total landfilled C stocks for a given year, the following were estimated: (1) The composition of the yard trimmings; (2) the mass of yard trimmings and food scraps discarded in landfills; (3) the C storage factor of the landfilled yard trimmings and food scraps; and (4) the rate of decomposition of the degradable C. 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 C storage factor (i.e., moisture content and C 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 *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: 2012 Facts and Figures* (EPA 2014a), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2008 and 2010 through 2012. To provide data for some of the missing years, detailed backup data were obtained from historical data tables that EPA developed for 1960 through 2012 (EPA 2014b). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Data for 2013 are not yet available, so they were set equal to 2012 values. The EPA (2014a) report and historical data tables (EPA 2014b) do not subdivide the discards (i.e., total generated minus composted) of individual materials into masses landfilled and combusted, although it provides a mass of overall waste stream discards managed in landfills[52] and combustors with energy recovery (i.e., ranging from 67 percent and 33 percent, respectively, in 1960 to 92 percent and 8 percent, respectively, in 1985); it is assumed that the proportion of each individual material (food scraps, grass, leaves, branches) that is landfilled is the same as the proportion across the overall waste stream.

The amount of C 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) C 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 C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 6-51).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid sample can be expressed as a proportion of initial C (shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-51).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C 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. (The CH_4 emissions resulting from decomposition of yard trimmings and food scraps are accounted for in the *Waste* chapter.) The degradable portion of the C is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-51.

The first-order decay rates, *k*, for each component were 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 found so that the weighted average decay rate for all components is equal to the AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually. Because AP-42 values were developed using landfill data from approximately 1990, 1990 waste composition for the United States from EPA's *Characterization of Municipal Solid Waste in the United States: 1990 Update* was used to calculate *f*. This correction factor is then multiplied by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.

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[52] EPA (2014) reports discards in two categories: "combustion with energy recovery" and "landfill, other disposal," which includes combustion without energy recovery. For years in which there is data from previous EPA reports on combustion without energy recovery, EPA assumes these estimates are still applicable. For 2000 to present, EPA assumes that any combustion of MSW that occurs includes energy recovery, so all discards to "landfill, other disposal" are assumed to go to landfills.

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 found, 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). The *Landfills* section of the Inventory (which estimates CH_4 emissions) estimates the overall MSW decay rate 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 methodologies across the Inventory, the correction factors (f) were developed for decay rates of 0.038 and 0.057 $year^{-1}$ through linear interpolation. A weighted national average component-specific decay rate was 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 component-specific decay rates are shown in Table 6-51.

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to the following formula:

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

where,

t = Year for which C stocks are being estimated (year),
i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$ = Stock of C 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 C that is stored for waste i (percent),
ICC_i = Initial C 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 C in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year t is calculated as the change in stock compared to the preceding year:

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, the C placed in a landfill in year n is tracked for each year t through the end of the inventory period (2013). For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C. 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 (518,000 metric tons) decomposes, leaving a total of 617,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2013, the total food scraps C originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed of in subsequent years (1961 through 2013), the total landfill C from food scraps in 2013 was 40.8 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2013, yielding a value of 262.0 million metric tons (as shown in Table 6-52). In exactly the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 6-50) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2013 shown in Table 6-50 (3.4 MMT C) is equal to the stock in 2013 (262.1 MMT C) minus the stock in 2012 (258.6 MMT C).

The C stocks calculated through this procedure are shown in Table 6-52.

Table 6-51: Moisture Contents, C Storage Factors (Proportions of Initial C 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 ($year^{-1}$)	0.323	0.185	0.016	0.156

Table 6-52: C Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2009	2010	2011	2012	2013
Yard Trimmings	**155.8**	**202.9**	**211.0**	**213.6**	**216.1**	**218.7**	**221.2**
Branches	14.5	18.1	18.8	19.0	19.3	19.5	19.8
Leaves	66.7	87.3	91.1	92.2	93.4	94.5	95.7
Grass	74.6	97.5	101.2	102.3	103.5	104.6	105.7
Food Scraps	**17.6**	**32.8**	**36.9**	**38.0**	**39.0**	**39.9**	**40.8**
Total Carbon Stocks	**173.5**	**235.6**	**248.0**	**251.6**	**255.1**	**258.6**	**262.1**

Uncertainty and Time-Series Consistency

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 C), initial C content, moisture content, decay rate, and proportion of C stored. The C 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. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-53. Total yard trimmings and food scraps CO_2 flux in 2013 was estimated to be between -19.3 and -4.9 MMT CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 53 percent below to 61 percent above the 2013 flux estimate of -12.6 MMT CO_2 Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

Table 6-53: 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	2013 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
Yard Trimmings and Food Scraps	CO_2	(12.6)	(19.3)	(4.9)	-53%	+61%

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net C sequestration.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The current Inventory has been revised relative to the previous report. Generation and recovery data for yard trimmings and food scraps was not previously provided for every year from 1960 in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* report. EPA has since released historical data, which included data for each year from 1960 through 2012. The recalculations based on these historical data resulted in changes ranging from a 17 percent increase in sequestration in 1996 to a 5 percent decrease in sequestration in 2005, and an average 4 percent increase in sequestration across the 1990–2012 time series compared to the previous Inventory.

Planned Improvements

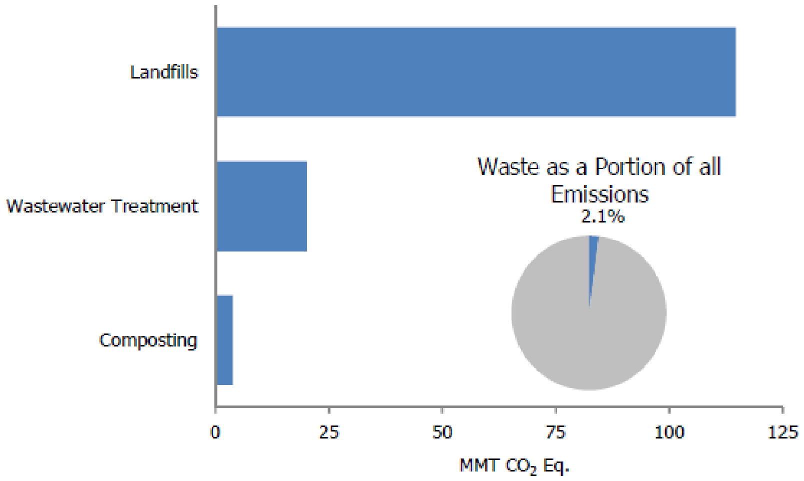
Future work is planned to evaluate the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH_4 emissions described in the *Waste* chapter. For example, the *Waste* chapter does not distinguish landfill CH_4 emissions from yard trimmings and food scraps separately from landfill CH_4 emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills accounted for approximately 18.0 percent of total U.S. anthropogenic methane (CH_4) emissions in 2013, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 2.4 percent and less than 1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. N_2O emissions from composting were also estimated. Together, these waste activities account for less than 2 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 chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1: 2013 Waste Chapter Greenhouse Gas Sources

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.



Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks 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 2006).[1] Additionally, the calculated emissions and sinks in a given year for the United

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

States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[2] The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. Emissions and sinks provided in the current Inventory do not preclude alternative examinations,[3] but rather presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

Overall, in 2013, waste activities generated emissions of 138.3 MMT CO_2 Eq.,[4] or just over 2 percent of total U.S. greenhouse gas emissions.

Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CH_4	**202.3**	**183.2**	**175.5**	**139.1**	**138.4**	**132.4**	**131.6**
Landfills	186.2	165.5	158.1	121.8	121.3	115.3	114.6
Wastewater Treatment	15.7	15.9	15.6	15.5	15.3	15.2	15.0
Composting	0.4	1.9	1.9	1.8	1.9	1.9	2.0
N_2O	**3.7**	**6.0**	**6.3**	**6.4**	**6.5**	**6.6**	**6.7**
Domestic Wastewater Treatment	3.4	4.3	4.6	4.7	4.8	4.9	4.9
Composting	0.3	1.7	1.7	1.6	1.7	1.7	1.8
Total	**206.0**	**189.2**	**181.8**	**145.5**	**144.9**	**138.9**	**138.3**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
CH_4	**8,091**	**7,330**	**7,021**	**5,565**	**5,536**	**5,294**	**5,265**
Landfills	7,450	6,620	6,324	4,873	4,851	4,611	4,585
Wastewater Treatment	626	635	623	619	610	606	601
Composting	15	75	75	73	75	77	79
N_2O	**12**	**20**	**21**	**21**	**22**	**22**	**22**
Domestic Wastewater Treatment	11	15	16	16	16	16	17
Composting	1	6	6	5	6	6	6

Note: Totals may not sum due to independent rounding.

Carbon dioxide, 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

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[2] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

[3] For example, see <http://www.epa.gov/aboutepa/oswer.html>.

[4] Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

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 2013 resulted in 10.4 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 3.3.

The UNFCCC incorporated the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* as the standard for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This chapter presents emission estimates calculated in accordance with the methodological guidance provided in these guidelines.

Box 7-2: Waste Data from the Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. EPA published a rule for the mandatory reporting of greenhouse gases from large GHG emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). 40 CFR part 98 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 41 industrial categories. 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.

EPA's GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective planned improvements sections for source categories in this chapter, EPA is analyzing how to use facility-level GHGRP data to improve the national estimates presented in this Inventory. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. This may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. It should be noted that the definitions for source categories in the GHGRP may differ from those used in this Inventory in meeting the UNFCCC reporting guidelines. In line with the UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from source categories identified in the IPCC guidelines. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the EPA's GHGRP website.[5]

EPA presents the data collected by EPA's GHGRP through a data publication tool[6] that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.

7.1 Landfills (IPCC Source Category 5A1)

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 commonly 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 7-1 and Box 7-2. 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 7-3. 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 time frame of 1990 to 2013. 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.

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[5] See <http://www.ccdsupport.com/confluence/display/ghgp/Detailed+Description+of+Data+for+Certain+Sources+and+Processes>.

[6] See <http://ghgdata.epa.gov>.

Industrial waste landfills are constructed in a similar way as MSW landfills, but accept waste produced by industrial activity, such as factories, mills, and mines.

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 methane (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 by-products or volatilization of biodegradable wastes (EPA 2008).

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. However, the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines set an international convention to not report biogenic CO_2 released due to landfill decomposition in the Waste sector (IPCC 2006). Carbon dioxide emissions from landfills are estimated and reported under the Land Use/Land Use Change and Forestry (LULUCF) sector (see Box 7-4). Additionally, emissions of NMOC and VOC are not estimated because they are considered to be emitted in trace amounts. 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. N_2O 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* (IPCC 2006) 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 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., composition of waste-in-place, 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 passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills practice 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 commonly 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 disposed of in a landfill and will continue for 10 to 60 years or longer as the degradable waste decomposes over time.

In 2013, landfill CH_4 emissions were approximately 114.6 MMT CO_2 Eq. (4,585 kt), representing the third largest source of CH_4 emissions in the United States, behind natural gas systems and enteric fermentation. Emissions from MSW landfills, which received about 63 percent of the total solid waste generated in the United States (Shin 2014), accounted for approximately 95 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,900 to 2,000 operational MSW landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 emitted (EPA 2010; *BioCycle* 2010; WBJ 2010). 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, WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to approximately 2,000 in 2010, the average landfill size has increased (EPA 2014c; *BioCycle* 2010; WBJ 2010). The exact number of active and closed dedicated industrial waste landfills is not known at this time, but the Waste Business Journal total for landfills accepting industrial and construction and demolition debris for 2010 is 1,305 (WBJ 2010). Only 176 facilities with industrial waste landfills reported under subpart TT (Industrial Waste Landfills) of EPA's Greenhouse Gas Reporting Program (GHGRP) since reporting began in 2011, indicating that there may be several hundreds of industrial waste landfills that are not required to report under EPA's GHGRP, or that the actual number of industrial waste landfills in the United States is relatively low compared to MSW landfills.

The estimated annual quantity of waste placed in MSW landfills increased 26 percent from approximately 205 MMT in 1990 to 259 MMT in 2013 (see Annex 3.14). The annual amount of waste 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 total amount of MSW generated is expected to increase as the U.S. population continues to grow, but the percentage of waste landfilled may decline due to increased recycling and composting practices. The estimated quantity of waste placed in industrial waste landfills has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 10.7 MMT in 2013.

Net CH_4 emissions have fluctuated from year to year, but a slowly decreasing trend has been observed over the past decade despite increased waste disposal amounts. For example, from 1990 to 2013, net CH_4 emissions from landfills decreased by approximately 38 percent, from 7.4 MMT to 4.6 MMT (see Table 7-3). This decreasing trend can be attributed to a 21 percent reduction in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series (EPA 2010) and an increase in the amount of landfill gas collected and combusted (i.e., used for energy or flared) at MSW landfills, resulting in lower net CH_4 emissions from MSW landfills.[7] For instance, in 1990, approximately 491 kt of CH_4 were recovered and combusted from landfills, while in 2013, approximately 8,970 kt of CH_4 were recovered and combusted, representing an average annual increase in the quantity of CH_4 recovered and combusted at MSW landfills from 1990 to 2013 of 13 percent (see Annex 3.14). Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

The quantity of recovered CH_4 that is either flared or used for energy purposes at MSW landfills has continually increased as a result of 1996 federal regulations that require large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subpart Cc 2005 and 40 CFR Part 60, Subpart WWW 2005). Voluntary programs that encourage CH_4 recovery and beneficial reuse, such as EPA's Landfill Methane Outreach Program (LMOP) and federal and state incentives that promote renewable energy (e.g., tax credits, low interest loans, and Renewable Portfolio Standards), have also contributed to increased interest in landfill gas collection and control. In 2013, an estimated 16 new landfill gas-to-energy (LFGTE) projects (EPA 2014a) and 3 new flares began operation. While the amount of landfill gas collected and combusted continues to increase every year, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows.

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
MSW Landfills	205.4	287.4	316.4	321.5	325.7	329.1	332.6
Industrial Landfills	13.8	18.3	18.8	18.9	18.9	19.0	19.1
Recovered							
Gas-to-Energy	(8.0)	(56.4)	(81.7)	(170.2)	(174.8)	(184.4)	(188.9)
Flared	(4.2)	(65.4)	(78.0)	(34.8)	(35.1)	(35.6)	(35.3)
Oxidized[a]	(20.7)	(18.4)	(17.6)	(13.5)	(13.5)	(12.8)	(12.7)
Total	**186.2**	**165.5**	**158.1**	**121.8**	**121.3**	**115.3**	**114.6**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at municipal and industrial landfills.

Table 7-4: CH_4 Emissions from Landfills (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
MSW Landfills	8,215	11,498	12,657	12,860	13,030	13,166	13,303
Industrial Landfills	553	732	753	756	758	760	763
Recovered							
Gas-to-Energy	(321)	(2,256)	(3,266)	(6,809)	(6,991)	(7,377)	(7,557)
Flared	(170)	(2,618)	(3,119)	(1,393)	(1,406)	(1,426)	(1,414)
Oxidized[a]	(828)	(736)	(703)	(539)	(539)	(521)	(509)
Total	**7,450**	**6,620**	**6,324**	**4,873**	**4,851**	**4,611**	**4,585**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
[a] Includes oxidation at municipal and industrial landfills.

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[7] Due to a lack of data specific to industrial waste landfills, landfill gas recovery is only estimated for MSW landfills.

Methodology

CH_4 emissions from landfills were estimated as the CH_4 produced from MSW landfills, plus the CH_4 produced by industrial waste landfills, minus the CH_4 recovered and combusted from MSW landfills, minus the CH_4 oxidized before being released into the atmosphere:

$$\mathrm{CH}_{4,\mathrm{Solid\ Waste}} = [\mathrm{CH}_{4,\mathrm{MSW}} + \mathrm{CH}_{4,\mathrm{Ind}} - \mathrm{R}] - \mathrm{Ox}$$

where,

$CH_{4,Solid\ Waste}$ = CH_4 emissions from solid waste
$CH_{4,MSW}$ = CH_4 generation from MSW landfills,
$CH_{4,Ind}$ = CH_4 generation from industrial landfills,
R = CH_4 recovered and combusted (only for MSW landfills), and
Ox = CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere.

The methodology for estimating CH_4 emissions from landfills is based on the first order decay model described by the IPCC (IPCC 2006). Methane generation is based on nationwide waste disposal data; it is not landfill-specific. The amount of CH_4 recovered, however, is landfill-specific, but only for MSW landfills due to a lack of data specific to industrial waste landfills. Values for the CH_4 generation potential (L_0) and decay rate constant (k) used in the first order decay model were obtained from an analysis of CH_4 recovery rates for a database of 52 landfills and from published studies of other landfills (RTI 2004; EPA 1998; SWANA 1998; Peer, Thorneloe, and Epperson 1993). The decay rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall, or climate types (wet, arid, and temperate). The annual quantity of waste placed in landfills was apportioned to the 3 ranges of rainfall based on the percent of the U.S. population in each of the 3 ranges. Historical census data were used to account for the shift in population to more arid areas over time. An overview of the data sources and methodology used to calculate CH_4 generation and recovery is provided below, while a more detailed description of the methodology used to estimate CH_4 emissions from landfills can be found in Annex 3.14.

States and local municipalities across the United States do not consistently track and report quantities of generated or collected waste or their end-of-life disposal methods to a centralized system. Therefore, national MSW landfill waste generation and disposal data are obtained from secondary data, specifically the State of Garbage surveys, published approximately every two years, with the most recent publication date of 2014. The State of Garbage (SOG) survey is the only continually updated nationwide survey of waste disposed in landfills in the United States and is the primary data source with which to estimate nationwide CH_4 emissions from MSW landfills. The SOG surveys use the principles of mass balance where all MSW generated is equal to the amount of MSW landfilled, combusted in waste-to-energy plants, composted, and/or recycled (*BioCycle* 2010; Shin 2014). This approach assumes that all waste management methods are tracked and reported to state agencies. Survey respondents are asked to provide a breakdown of MSW generated and managed by landfilling, recycling, composting, and combustion (in waste-to-energy facilities) in actual tonnages as opposed to reporting a percent generated under each waste disposal option. The data reported through the survey have typically been adjusted to exclude non-MSW materials (e.g., industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. In the most recent survey, state agencies were asked to provide already filtered, MSW-only data. Where this was not possible, they were asked to provide comments to better understand the data being reported. All state disposal data are adjusted for imports and exports across state lines where imported waste is included in a particular state's total while exported waste is not. Methodological changes have occurred over the time frame the SOG survey has been published, and this has affected the fluctuating trends observed in the data (RTI 2013).

The SOG survey is voluntary and not all states provide data for each survey year. Where no waste generation data are provided by a state in the SOG survey, the amount generated is estimated by multiplying the waste per capita from a previous SOG survey by that particular state's population. If that particular state did not report any waste generation data in the previous SOG survey, the average nationwide waste per capita rate for the current SOG survey is multiplied by that particular state's population. The quantities of waste generated across all states are summed and that value is then used as the nationwide quantity of waste generated in a given reporting year.

State-specific landfill waste generation data and a national average disposal factor for 1989 through 2008 were obtained from the SOG survey for every two years (i.e., 2002, 2004, 2006, and 2008 as published in BioCycle 2006, 2008, and 2010). The most recent SOG survey provides data for 2011 (Shin 2014). State-specific landfill waste generation data for the years in-between the SOG surveys (e.g., 2001, 2003, 2005, 2007, 2009, 2010, 2012, and 2013) were either interpolated or extrapolated based on the SOG data and the U.S. Census population data. Because the most recent SOG survey was published in 2014 for the 2011 year, the annual quantities of waste generated for the years 2012 and 2013 were extrapolated based on the 2011 data and population growth. Waste generation data will be updated as new reports are published. Because the SOG survey does not account for waste generated in U.S. territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2014) and national per capita solid waste generation from the SOG survey (Shin 2014).

Estimates of the quantity of waste landfilled from 1989 to 2013 are determined by applying a waste disposal factor to the total amount of waste generated (i.e., the SOG data). A waste disposal factor is determined for each year an SOG survey is published and equals the ratio of the total amount of waste landfilled to the total amount of waste generated. The waste disposal factor is interpolated for the years in-between the SOG surveys, as is done for the amount of waste generated for a given survey year.

Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the first order decay model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in the current Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (Methane Conversion Factor, MCF, of 1) and those disposed in dumps (MCF of 0.6). All calculations after 1980 assume waste is disposed in managed, modern landfills. Please see Annex 3.14 for more details.

Methane recovery is currently only accounted for at MSW landfills. Data collected through EPA's GHGRP for industrial waste landfills (subpart TT) show that only 2 of the 176 facilities, or 1 percent of facilities, reporting have active gas collection systems. EPA's GHGRP is not a national database and no comprehensive data regarding gas collection systems have been published for industrial waste landfills. Assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills, have not been made for the Inventory methodology.

The estimated landfill gas recovered per year (R) at MSW landfills was based on a combination of four databases and grouped into recovery from flares and recovery from landfill gas-to-energy (LFGTE) projects:

- the flare vendor database (contains updated sales data collected from vendors of flaring equipment)
- a database of LFGTE projects compiled by LMOP (EPA 2014a)
- a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007), and
- EPA's GHGRP dataset for MSW landfills (EPA 2014b).

EPA's GHGRP MSW landfills database was first introduced as a data source for the current Inventory (i.e., the 1990-2013 Inventory report). EPA's GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification, thus it is considered to contain the least uncertain data of the four databases. However, this database is unique in that it only contains a portion of the landfills in the United States (although, presumably the highest emitters since only those landfills that meet a certain CH_4 generation threshold must report) and only contains data for 2010 and later.

The total amount of CH_4 recovered and destroyed was estimated using the four databases listed above. To avoid double- or triple-counting CH_4 recovery, the landfills across each database were compared and duplicates identified. A hierarchy of recovery data is used based on the certainty of the data in each database as described below.

For the years 2010 to 2013, if a landfill in EPA's GHGRP MSW landfills database was also in the EIA, LMOP, and/or flare vendor database, the avoided emissions were based on EPA's GHGRP MSW landfills database. For the years 1990 to 2009, if a landfill in the EIA database was also in the LMOP and/or the flare vendor database, the emissions avoided were based on the EIA data because landfill owners or operators directly reported the amount of CH_4 recovered based on measurements of gas flow and concentration, and the reporting accounted for changes over time. However, as the EIA database only includes data through 2006, the amount of CH_4 recovered from 2007 to

2013 for projects included in the EIA database were assumed to be the same as in 2006. This quantity likely underestimates flaring because the EIA database does not have information on all flares in operation. If both flare data and LMOP recovery data were available for any of the remaining landfills (i.e., not in the EIA or GHGRP databases), then the avoided emissions were based on the LMOP data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare vendor database, on the other hand, estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity.

Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LMOP database was avoided by subtracting emission reductions associated with LFGTE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor). A further explanation of the methodology used to estimate the landfill gas recovered can be found in Annex 3.14.

The amount of landfill gas recovered and combusted is also presented in terms of avoided emissions by flaring and avoided emissions by LFGTE. The amount combusted by flaring was directly determined using information provided by the EIA and flare vendor databases and indirectly determined using information in EPA's GHGRP dataset for MSW landfills. Information provided by the EIA and LMOP databases were used to directly estimate methane combusted in LFGTE projects over the time series. EPA's GHGRP MSW landfills database provides a total amount of CH_4 recovered at the facility-level and was indirectly used to estimate methane combusted in LFGTE projects. Unlike the three other databases, EPA's GHGRP dataset does not identify whether the amount of CH_4 recovered is combusted by a flare versus an LFGTE project. Therefore, a mapping exercise was performed between EPA's GHGRP MSW landfills database and the three other databases to make a distinction between landfills contained in both EPA's GHGRP MSW landfills database and one or more of the other databases. The CH_4 recovered by landfills matched to the EIA (and marked as LFGTE) and LMOP databases was allocated as CH_4 recovered and combusted by LFGTE projects. The remaining CH_4 recovered from EPA's GHGRP dataset was allocated as CH_4 recovered and combusted by flares.

The destruction efficiencies reported through EPA's GHGRP were applied to the landfills in EPA's GHGRP MSW landfills database. The median value of the reported destruction efficiencies was 99 percent for all reporting years (2010 through 2013). A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided due to the combusting of CH_4 in destruction devices (i.e., flares) in the EIA, LMOP, and flare vendor databases. The 99 percent destruction efficiency value was selected based on the range of efficiencies (86 to 99+ percent) recommended for flares in EPA's AP-42 Compilation of Air Pollutant Emission Factors, Draft Chapter 2.4, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non- CH_4 components (i.e., volatile organic compounds and non-methane organic compounds) in test results (EPA 2008). An arithmetic average of 98.3 percent and a median value of 99 percent are derived from the test results presented in EPA (2008). Thus, a value of 99 percent for the destruction efficiency of flares has been used in Inventory methodology. Other data sources supporting a 99 percent destruction efficiency include those used to establish New Source Performance Standards (NSPS) for landfills and in recommendations for shutdown flares used in the LMOP.

Emissions from industrial waste landfills were estimated from industrial production data (ERG 2014), waste disposal factors, and the first order decay model. As over 99 percent of the organic waste placed in industrial waste landfills originated from the food processing (meat, vegetables, fruits) and pulp and paper industries, estimates of industrial landfill emissions focused on these two sectors (EPA 1993). There are currently no data sources that track and report the amount and type of waste disposed of in industrial waste landfills in the United States. Therefore, 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. 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 CH_4 oxidized by the landfill cover at both municipal and industrial waste landfills was assumed to be 10 percent of the CH_4 generated that is not recovered (IPCC 2006, Mancinelli and McKay 1985, Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial waste landfills.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH_4 production: the amount and composition of waste placed in every MSW and industrial waste landfill for each year of its operation. The SOG survey is the only nationwide data source that compiles the amount of MSW disposed at the state-level. The surveys do not include information on waste composition and there are no comprehensive data sets that compile quantities of waste disposed or waste composition by landfill. EPA's GHGRP does allow facilities to report annual quantities of waste disposed by composition, but very few do so. Additionally, some MSW landfills have conducted detailed waste composition studies, but because landfills in the United States are not required to perform these types of studies, the data are scarce over the time series and across the country.

The approach used here assumes that the CH_4 generation potential and the rate of decay that produces CH_4, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. 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, this approach may over- and under-estimate CH_4 generation at some landfills if used at the facility-level, but the end result is expected to balance out because it is being applied nationwide. There is also a high degree of uncertainty and variability associated with the first order decay model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006).

Additionally, there is a lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States. The approach used here assumes that the majority (99 percent) of industrial waste disposed of in industrial waste landfills consists of waste from the pulp and paper and food and beverage industries. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, we apply a straight disposal factor over the entire time series to the amount of waste generated to determine the amounts disposed.

Aside from the uncertainty in estimating CH_4 generation potential, uncertainty also exists in the estimates of the landfill gas oxidized. A constant oxidation factor of 10 percent as recommended by the Intergovernmental Panel on Climate Change (IPCC) for managed landfills is used for both MSW and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system. The number of field studies measuring the rate of oxidation has increased substantially since the *IPCC 2006 Guidelines* were published and, as discussed in the Potential Improvements section, efforts are being made to review the literature and revise this value based on recent, peer-reviewed studies.

Another significant source of uncertainty lies with the estimates of CH_4 that are recovered by flaring and gas-to-energy projects at MSW landfills. Until the current Inventory, three separate databases containing recovery information were used to determine the total amount of CH_4 recovered and there are uncertainties associated with each. For the current Inventory, EPA's GHGRP MSW landfills database was added as a fourth recovery database. Relying on multiple databases for a complete picture introduces uncertainty because the coverage of each database differs, which increases the chance of double counting avoided emissions. Additionally, 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; in reality, the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered.

The LMOP database and the flare vendor databases are updated annually. The EIA database has not been updated since 2005 and, for the most part, was replaced by EPA's GHGRP MSW landfills database for the portion of landfills reporting under EPA's GHGRP (i.e., those meeting the GHGRP thresholds) that were also included in the EIA database. 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. EPA's GHGRP data are given precedence because CH_4 recovery is directly reported by landfills and undergoes a rigorous verification process; the EIA data are given second priority because facility data were directly reported; the LMOP data are given third priority because CH_4 recovery is estimated from facility-reported LFGTE system characteristics; and the flare data are given fourth priority because this database contains minimal information about the flare and no site-specific operating characteristics (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 IPCC default value of 10 percent for uncertainty in recovery estimates was used for 2 of the 4 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 EIA and LMOP databases. A lower uncertainty value (5 percent) was applied to the GHGRP MSW landfills dataset as a result of the supporting information provided and verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of approximately 50 percent was used. The compounding uncertainties associated with the 4 databases in addition to the uncertainties associated with the first order decay model and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5. Industrial waste landfills are shown with a lower range of uncertainty due to the smaller number of data sources and associated uncertainty involved. For example, 3 data sources are used to generate the annual quantities of MSW waste disposed over the 1940 to current year, while industrial waste landfills rely on 2 data sources.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. In 2013, landfill CH_4 emissions were estimated to be between 60.7 and 217.4 MMT CO_2 Eq., which indicates a range of 47 percent below to 90 percent above the 2013 emission estimate of 114.6 MMT CO_2 Eq.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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
Landfills	**CH_4**	**114.6**	**60.7**	**217.4**	**-47%**	**+90%**
MSW	CH_4	97.5	45.0	201.0	-54%	+106%
Industrial	CH_4	17.2	12.2	21.3	-29%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are performed for the transcription of the published data set used to populate the Inventory data set, including the SOG survey data and the published LMOP database, but are not performed on the data itself against primary data used. A primary focus of the QA/QC checks was to ensure that CH_4 recovery estimates were not double-counted and that all LFGTE projects and flares were included in the respective project databases. Both manual and electronic checks were used to ensure that emission avoidance from each landfill was calculated only once. The primary calculation spreadsheet is tailored from the IPCC waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values were verified by secondary QA/QC review.

Recalculations Discussion

Three major methodological recalculations were performed for the current Inventory. First, a new SOG survey was published allowing for the update of the annual quantities of waste generated and disposed and the amount of CH_4 generated for the years 2009 through 2012. Second, the percent of the U.S. population within the three precipitation ranges were updated for the year 2010 (see Table A-3 in Annex 3.14), which impacted the distribution for the years 2001 through 2013 in the waste model. Third, the EPA's GHGRP CH_4 recovery and destruction efficiency data were incorporated. Further discussion on the recalculations made are discussed below.

Beginning in 2011, all MSW landfills that accepted waste on or after January 1, 1980 and generate CH_4 in amounts equivalent to 25,000 metric tons or more of carbon dioxide equivalent (CO_2 Eq.) are required to calculate and report their greenhouse gas emissions to EPA through its GHGRP. The data reported in one year represent the GHGs that the landfill generated and emitted in the previous calendar year. As a result EPA now has data from 2010 through 2013 for MSW landfills. The MSW landfill source category of EPA's GHGRP consists of the landfill, landfill gas collection systems, and landfill gas destruction devices, including flares. For the current Inventory year, the annual quantity of CH_4 recovered and the destruction efficiency of the flare and/or LFGTE system at each facility were incorporated as a fourth CH_4 recovery database (i.e., the GHGRP MSW landfills database). The GHGRP data undergo an extensive series of verification steps, are more reliable and accurate than the data currently used in the three other CH_4 recovery databases (Bronstein et al. 2012). A significant effort was made to compare the unique landfills in each database to ensure the hierarchy of recovery was maintained (i.e., GHGRP > EIA > LMOP > flare database) and that double, or triple counting was not encountered.

Facility-level reporting data from EPA's GHGRP are not available for the entire time series reported in the current Inventory; therefore, particular attention was made to ensure time series consistency while incorporating data from EPA's GHGRP. 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 was relied upon.[8] However, after incorporating the GHGRP MSW landfills data, a significant drop in net CH_4 emissions from 2009 to 2010 was observed (see Table 7-3 and Table 7-4). The underlying reason(s) for the large increase in the CH_4 recovered and the large decrease in net emissions is being investigated and may most likely result from the flare database underestimating the amount of CH_4 recovered as a result of the midpoint in each flare's reported capacity being used in the recovery calculations.

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for these greenhouse gases. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Planned Improvements

Improvements being examined include incorporating additional data from recent peer-reviewed literature to modify the default oxidation factor applied to MSW and industrial waste landfills (currently 10 percent), and to either modify the bulk waste degradable organic carbon (DOC) value or estimate emissions using a waste-specific approach in the first order decay model using data from the GHGRP and peer-reviewed literature.

A standard CH_4 oxidation factor of 10 percent has been used for both industrial and MSW landfills in prior Inventory reports and is currently recommended as the default for well-managed landfills in the latest IPCC guidelines (2006). Recent comments on the Inventory methodology indicated that a default oxidation factor of 10 percent may be less than oxidation rates achieved at well-managed landfills with gas collection and control. As a first step toward revising this oxidation factor, a literature review was conducted in 2011 (RTI 2011). In addition, facilities reporting under EPA's GHGRP have the option to use an oxidation factor other than 10 percent (e.g., 0, 25, or 35 percent) if the calculated result of methane flux calculations warrants it. Various options are being investigated to incorporate this facility-specific data for landfills reporting under EPA's GHGRP and or the remaining facilities.

The standard oxidation factor (10 percent) is applied to the total amount of waste generated nationwide. Changing the oxidation factor and calculating the amount of CH_4 oxidized from landfills with gas collection and control requires the estimation of waste disposed in these types of landfills. The Inventory methodology uses waste generation data from the SOG surveys, which report the total amount of waste generated and disposed nationwide by state. In 2010, the State of Garbage survey requested data on the presence of landfill gas collection systems for the first time. Twenty-eight states reported that 260 out of 1,414 (18 percent) operational landfills recovered landfill gas (*BioCycle* 2010). However, the survey did not include closed landfills with gas collection and control systems. In the future, the amount of states collecting and reporting this information is expected to increase. GHGRP data for MSW landfills could be used to fill in the gaps related to the amount of waste disposed in landfills with gas collection systems. Although EPA's GHGRP does not capture every landfill in the United States, larger landfills are expected to meet the reporting thresholds and will be reporting waste disposal information by year beginning in

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[8] See: <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

March 2013. After incorporating EPA's GHGRP data, it may be possible to calculate the amount of waste disposed of at landfills with and without gas collection systems in the United States, which will allow the inventory waste model to apply different oxidation factors depending on the presence of a gas collection system.

Other potential improvements to the methodology may be made in the future using other portions of EPA's GHGRP dataset, specifically for inputs to the first order decay equation. The approach used in the Inventory to estimate CH_4 generation assumes a bulk waste-specific DOC value that may not accurately capture the changing waste composition over the time series (e.g., the reduction of organics entering the landfill environment due to increased composting, see Box 7-2). Using data obtained from EPA's GHGRP and any publicly available landfill-specific waste characterization studies in the United States, the methodology may be modified to incorporate a waste composition approach, or revisions may be made to the bulk waste DOC value currently used. Additionally, GHGRP data could be analyzed and a weighted average for the CH_4 correction factor (MCF), fraction of CH_4 (F) in the landfill gas, the destruction efficiency of flares, and the decay rate constant (k) could replace the values currently used in the Inventory.

In addition to MSW landfills, industrial waste landfills at facilities emitting CH_4 in amounts equivalent to 25,000 metric tons or more of CO_2 Eq. were required to report their GHG emissions beginning in September 2012 through EPA's GHGRP. Similar data for industrial waste landfills as is required for the MSW landfills are being reported. Any additions or improvements to the Inventory using reported GHGRP data will be made for the industrial waste landfill source category. One potential improvement includes a revision to the waste disposal factor currently used by the Inventory for the pulp and paper sector using production data from pulp and paper facilities that reported annual production and annual disposal data under EPA's GHGRP. Another possible improvement is the addition of industrial sectors other than pulp and paper, and food and beverage (e.g., metal foundries, petroleum refineries, and chemical manufacturing facilities). Of particular interest in EPA's GHGRP data set for industrial waste landfills is the presence of gas collection systems since recovery is not currently associated with industrial waste landfills in the Inventory methodology. It is unlikely that data reported through EPA's GHGRP for industrial waste landfills will yield improved estimates for k and L_o for the industrial sectors. However, EPA is considering an update to the L_o and k values for the pulp and paper sector and will work with stakeholders to gather data and other feedback on potential changes to these values. The addition of this higher tier data will improve the emission calculations to provide a more accurate representation of greenhouse gas emissions from industrial waste landfills.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste generated in the United States can be managed through landfilling, recycling, composting, and combustion with energy recovery. There are two main sources for nationwide solid waste management data in the United States,

- The *BioCycle* and Earth Engineering Center of Columbia University's State of Garbage (SOG) in America surveys and
- The EPA's Municipal Solid Waste in The United States: Facts and Figures reports.

The SOG surveys collect state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. The survey asks 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 is not available, the survey asks for total tons landfilled. The data are adjusted for imports and exports across state lines so that the principles of mass balance are adhered to, whereby the amount of waste managed does not exceed the amount of waste generated. The SOG reports present survey data aggregated to the state level.

The EPA Facts and Figures reports use a materials flow methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, or discarded nationwide. The amount of MSW generated is estimated by adjusting the imports and exports of produced materials to other countries. MSW that is not recycled, composted, or combusted is assumed to be landfilled. The data presented in the report are nationwide totals.

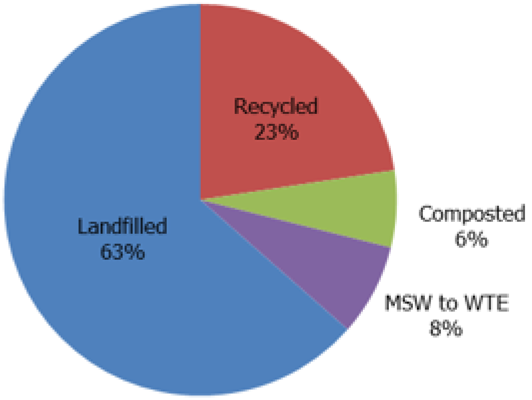
The State of Garbage surveys are the preferred data source for estimating waste generation and disposal amounts in the Inventory because they are considered a more objective, numbers-based analysis of solid waste management in the United States. However, the EPA Facts and Figures reports are useful when investigating waste management trends at the nationwide level and for typical waste composition data, which the State of Garbage surveys do not request.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. 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, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting chapters in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report.

Box 7-4: Overview of the Waste Sector

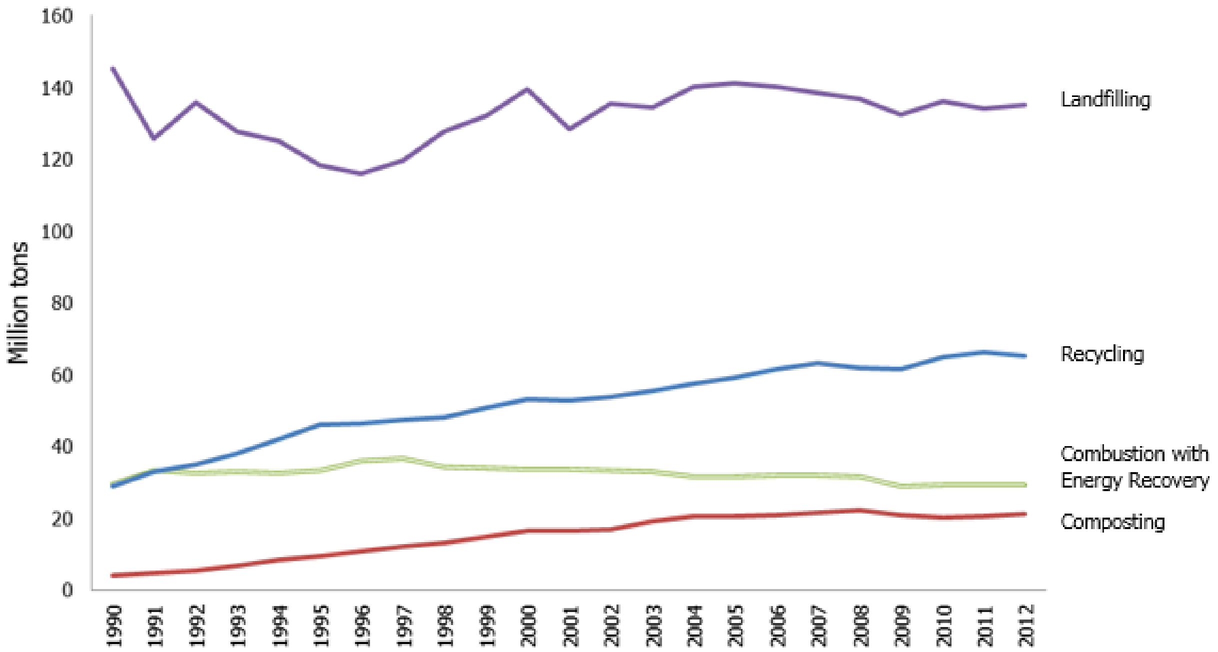
As shown in Figure 7-2 and Figure 7-3, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have normally been disposed of in a landfill.

Figure 7-2: Management of Municipal Solid Waste in the United States, 2011



Source: Shin 2014

Figure 7-3: MSW Management Trends from 1990 to 2012



Source: EPA 2014c

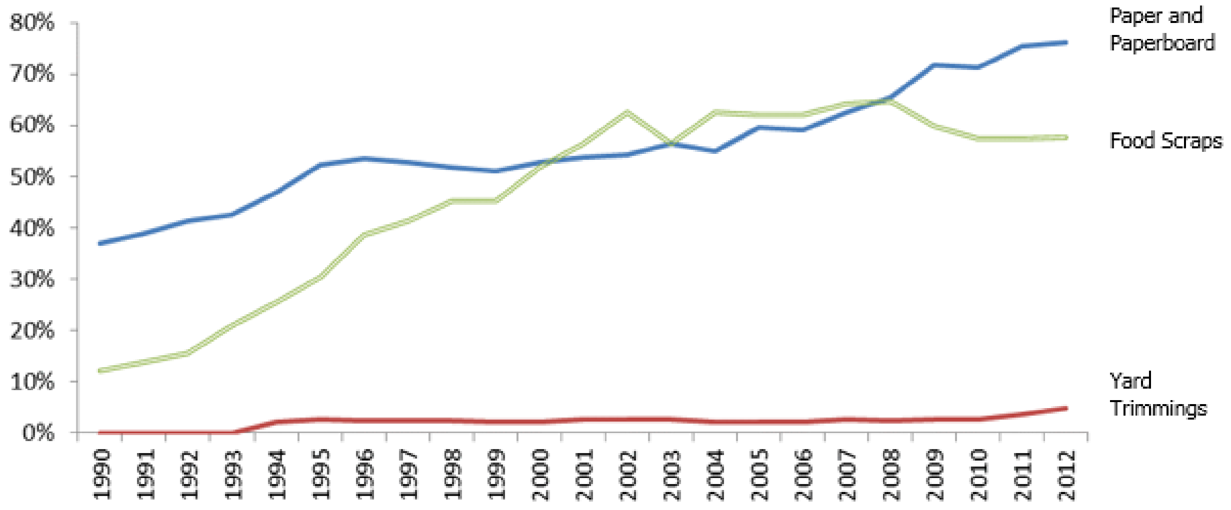
Table 7-6 presents a typical composition of waste disposed of at a typical MSW landfill in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6. Understanding how the waste composition changes over time, specifically for the degradable waste types, is important for estimating greenhouse gas emissions. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste recovery, including recycling and composting (see Table 7-6 and Figure 7-4). Landfill ban legislation affecting yard trimmings resulted in an increase of composting from 1990 to 2008. Table 7-6 and Figure 7-4 do not reflect the impact of backyard composting on yard trimming generation and recovery estimates. The recovery of food trimmings has been consistently low. Increased recovery of degradable materials reduces the CH_4 generation potential and CH_4 emissions from landfills.

Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type (Percent)

Waste Type	1990	2005	2009	2010	2011	2012
Paper and Paperboard	30.0%	24.5%	14.8%	16.2%	14.8%	14.8%
Glass	6.0%	5.7%	5.0%	5.1%	5.1%	5.1%
Metals	7.2%	7.7%	8.0%	8.8%	8.9%	9.0%
Plastics	9.6%	15.7%	15.8%	17.4%	17.8%	17.6%
Rubber and Leather	3.1%	3.5%	3.7%	3.7%	3.8%	3.8%
Textiles	2.9%	5.5%	6.3%	6.7%	6.8%	7.4%
Wood	6.9%	7.4%	7.7%	8.1%	8.2%	8.2%
Other[a]	1.4%	1.8%	1.9%	2.0%	2.0%	2.0%
Food Scraps[b]	13.6%	17.9%	19.1%	21.0%	21.4%	21.1%
Yard Trimmings[c]	17.6%	7.0%	7.6%	8.6%	8.8%	8.7%
Miscellaneous Inorganic Wastes	1.7%	2.1%	2.2%	2.3%	2.4%	2.4%

[a] Includes electrolytes in batteries and fluff pulp, feces, and urine in disposable diapers. Details may not add to totals due to rounding. Source: EPA 2014c.
[b] Data for food scraps were estimated using sampling studies in various parts of the country in combination with demographic data on population, grocery store sales, restaurant sales, number of employees, and number of prisoners, students, and patients in institutions. Source: EPA 2014c.
[c] Data for yard trimmings were estimated using sampling studies, population data, and published sources documenting legislation affecting yard trimmings disposal in landfills. Source: EPA 2014c.

Figure 7-4: Percent of Recovered Degradable Materials from 1990 to 2012 (Percent)



Source: EPA 2014c

Box 7-5: Description of a Modern, Managed Landfill

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. 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 New Source Performance Standards (NSPS) 40 CFR Part 60 Subpart WWW. Additionally, state and tribal requirements may exist.[9]

7.2 Wastewater Treatment (IPCC Source Category 5D)

Wastewater treatment processes can produce anthropogenic CH_4 and N_2O emissions. Wastewater from domestic[10] and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur on site, most commonly through septic systems or package plants, or off site at centralized treatment systems. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. In the United States, approximately 20 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 2011).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of N_2O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the N present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). N_2O can be an intermediate product of both processes, but has typically been associated with denitrification. Recent research suggests that higher emissions of N_2O may in fact originate from nitrification (Ahn et al. 2010). Other more recent research suggests that N_2O may also result from other types of wastewater treatment operations (Chandran 2012).

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

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[9] For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

[10] Throughout the inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

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). Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production. 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.

In 2013, CH_4 emissions from domestic wastewater treatment were 9.2 MMT CO_2 Eq. (368 kt CH_4). Emissions remained fairly steady from 1990 through 1997, but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004, U.S. Census 2011). In 2013, CH_4 emissions from industrial wastewater treatment were estimated to be 5.8 MMT CO_2 Eq. (233 kt CH_4). Industrial emission sources have generally increased across the time series through 1999 and then fluctuated up and down with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries. Table 7-7 and Table 7-8 provide CH_4 and N_2O emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, the United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes, and emissions from effluent from centralized treatment systems that has been discharged into aquatic environments. The 2013 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 MMT CO_2 Eq. (1 kt N_2O) and 4.6 MMT CO_2 Eq. (15 kt N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 4.9 MMT CO_2 Eq. (17 kt N_2O). N_2O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
CH_4	**15.7**	**15.9**	**15.6**	**15.5**	**15.3**	**15.2**	**15.0**
Domestic	10.5	10.0	9.8	9.6	9.4	9.3	9.2
Industrial[a]	5.1	5.8	5.8	5.9	5.9	5.8	5.8
N_2O	**3.4**	**4.3**	**4.6**	**4.7**	**4.8**	**4.9**	**4.9**
Domestic	3.4	4.3	4.6	4.7	4.8	4.9	4.9
Total	**19.1**	**20.2**	**20.2**	**20.2**	**20.1**	**20.1**	**19.9**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

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	2009	2010	2011	2012	2013
CH_4	**626**	**635**	**623**	**619**	**610**	**606**	**601**
Domestic	421	401	392	384	375	373	368
Industrial[a]	206	234	231	235	235	233	233
N_2O	**11**	**15**	**16**	**16**	**16**	**16**	**17**
Domestic	11	15	16	16	16	16	17

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed or that are designed to have periods of anaerobic activity (e.g., constructed wetlands), anaerobic systems (anaerobic lagoons and facultative lagoons), and from anaerobic digesters when the captured biogas is not completely combusted. CH_4 emissions from septic systems were estimated by multiplying the United States population by the percent of wastewater treated in septic systems (about 20 percent) and an emission factor (10.7 g CH_4/capita/day), and then converting the result to kt/year. CH_4emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (about 80 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the relative percentage of wastewater facilities with primary treatment, the percentage of BOD_5 treated after primary treatment (67.5 percent), the maximum CH_4-producing capacity of domestic wastewater (0.6), and the relative MCFs for well-managed aerobic (zero), not well managed aerobic (0.3), and anaerobic (0.8) systems with all aerobic systems assumed to be well-managed. CH_4emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH_4 in digester biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4), and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99). The methodological equations are:

Emissions from Septic Systems = A
= US_{POP} × (% onsite) × (EF_{SEPTIC}) × 1/10^9 × Days

Emissions from Centrally Treated Aerobic Systems = B
= [(% collected) × (total BOD_5 produced) × (% aerobic) × (% aerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% aerobic) × (% aerobic w/primary) × (1-% BOD removed in prim. treat.)] × (% operations not well managed) × (B_o) × (MCF-aerobic_not_well_man)

Emissions from Centrally Treated Anaerobic Systems = C
= [(% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/out primary) + (% collected) × (total BOD_5 produced) × (% anaerobic) × (% anaerobic w/primary) × (1-%BOD removed in prim. treat.)] × (B_o) × (MCF-anaerobic)

Emissions from Anaerobic Digesters = D
= [(POTW_flow_AD) × (digester gas)/ (per capita flow)] × conversion to m^3 × (FRAC_CH_4) × (365.25) × (density of CH_4) × (1-DE) × 1/10^9

Total CH_4 Emissions (kt) = A + B + C + D

where,

US_{POP} = U.S. population
% onsite = Flow to septic systems / total flow
% collected = Flow to POTWs / total flow
% aerobic = Flow to aerobic systems / total flow to POTWs
% anaerobic = Flow to anaerobic systems / total flow to POTWs
% aerobic w/out primary = Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary = Percent of aerobic systems that employ primary treatment
% BOD removed in prim. treat. = 32.5%
% operations not well managed = Percent of aerobic systems that are not well managed and in which some anaerobic degradation occurs
% anaerobic w/out primary = Percent of anaerobic systems that do not employ primary treatment
% anaerobic w/primary = Percent of anaerobic systems that employ primary treatment
EF_{SEPTIC} = Methane emission factor (10.7 g CH_4/capita/day) – septic systems
Days = days per year (365.25)

Total BOD_5 produced = kg BOD/capita/day × U.S. population × 365.25 days/yr
B_o = Maximum CH_4-producing capacity for domestic wastewater (0.60 kg CH_4/kg BOD)
1/10^6 = Conversion factor, kg to kt
MCF-aerobic_not_well_man. = CH_4 correction factor for aerobic systems that are not well managed (0.3)
MCF-anaerobic = CH_4 correction factor for anaerobic systems (0.8)
DE = CH_4 destruction efficiency from flaring or burning in engine (0.99 for enclosed flares)
POTW_flow_AD = Wastewater influent flow to POTWs that have anaerobic digesters (MGD)
digester gas = Cubic feet of digester gas produced per person per day (1.0 ft^3/person/day)
per capita flow = Wastewater flow to POTW per person per day (100 gal/person/day)
conversion to m^3 = Conversion factor, ft^3 to m^3 (0.0283)
FRAC_CH_4 = Proportion CH_4 in biogas (0.65)
density of CH_4 = 662 (g CH_4/m^3 CH_4)
1/10^9 = Conversion factor, g to kt

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2014) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. Table 7-9 presents U.S. population and total BOD_5 produced for 1990 through 2013, while Table 7-10 presents domestic wastewater CH_4 emissions for both septic and centralized systems in 2013. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, and 2011 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2011), with data for intervening years obtained by linear interpolation and data for 2013 forecasted using 1990-2012 data. The percent of wastewater flow to aerobic and anaerobic systems, the percent of aerobic and anaerobic systems that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 Clean Watershed Needs Survey (EPA 1992, 1996, 2000, and 2004). Data for intervening years were obtained by linear interpolation and the years 2004 through 2013 were forecasted from the rest of the time series. The BOD_5 production rate (0.09 kg/capita/day) and the percent BOD_5 removed by primary treatment for domestic wastewater were obtained from Metcalf and Eddy (2003). The maximum CH_4-producing capacity (0.6 kg CH_4/kg BOD_5) and both MCFs used for centralized treatment systems were taken from IPCC (2006), while the CH_4 emission factor (10.7 g CH_4/capita/day) used for septic systems were taken from Leverenz et al. (2010). The CH_4 destruction efficiency for methane recovered from sludge digestion operations, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4 (EPA 1998), efficiencies used to establish New Source Performance Standards (NSPS) for landfills, along with data from CAR (2011), Sullivan (2007), Sullivan (2010), and UNFCCC (2012). The cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) and the proportion of CH_4 in biogas (0.65) come from Metcalf and Eddy (2003). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, "Recommended Standards for Wastewater Facilities (Ten-State Standards)" (2004).

Table 7-9: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (kt)

Year	Population	BOD_5
1990	253	8,333
2005	300	9,853
2009	311	10,220
2010	313	10,303
2011	316	10,377
2012	318	10,452
2013	320	10,534

Sources: U.S. Census Bureau (2014);
Metcalf & Eddy (2003).

Table 7-10: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2013)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems	6.0	65.5%
Centralized Systems (including anaerobic sludge digestion)	3.2	34.5%
Total	**9.2**	**100%**

Note: Emission values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.

Industrial Wastewater CH_4 Emission Estimates

Methane emission estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). 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 these industries are whether they generate 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 five industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; and petroleum refining. Wastewater treatment emissions for these sectors for 2013 are displayed in Table 7-11 below. Table 7-12 contains production data for these industries.

Table 7-11: Industrial Wastewater CH_4 Emissions by Sector (2013)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	4.4	75%
Pulp & Paper	1.1	18%
Fruit & Vegetables	0.1	2%
Petroleum Refineries	0.1	2%
Ethanol Refineries	0.1	2%
Total	**5.8**	**100%**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.
Note: Totals may not sum due to independent rounding.

Table 7-12: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, and Petroleum Refining Production (MMT)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.5	702.4
2005	138.5	31.4	25.1	42.9	11.7	818.6
2009	120.4	33.8	25.2	46.5	32.7	822.4
2010	128.6	33.7	25.9	43.2	39.7	848.6
2011	127.5	33.8	26.2	44.3	41.6	858.8
2012	127.0	33.8	26.1	45.3	39.5	856.1
2013	131.5	33.6	26.5	43.9	39.8	875.9

[a] Pulp and paper production is the sum of woodpulp production plus paper and paperboard production.
Sources: Lockwood-Post (2002); FAO (2014); USDA (2014a); RFA (2014); EIA (2014).

CH_4 emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the maximum CH_4 producing potential of industrial wastewater (B_o), and the percentage of organic loading assumed to degrade anaerobically in a given treatment system (MCF). Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH_4/kg COD (IPCC 2006).

For each industry, the percent of plants in the industry that treat wastewater on site, the percent of plants that have a primary treatment step prior to biological treatment, and the percent of plants that treat wastewater anaerobically were defined. The percent of wastewater treated anaerobically onsite (TA) was estimated for both primary treatment ($\%TA_p$) and secondary treatment ($\%TA_s$). For plants that have primary treatment in place, an estimate of COD that is removed prior to wastewater treatment in the anaerobic treatment units was incorporated. The values used in the %TA calculations are presented in Table 7-13 below.

The methodological equations are:

$$CH_4 \text{ (industrial wastewater)} = [P \times W \times COD \times \%TA_p \times B_o \times MCF] + [P \times W \times COD \times \%TA_s \times B_o \times MCF]$$

$$\%TA_p = [\%Plants_o \times \%WW_{a,p} \times \%COD_p]$$

$$\%TA_s = [\%Plants_a \times \%WW_{a,s} \times \%COD_s] + [\%Plants_t \times \%WW_{a,t} \times \%COD_s]$$

where,

CH_4 (industrial wastewater) = Total CH_4 emissions from industrial wastewater (kg/year)
P = Industry output (metric tons/year)
W = Wastewater generated (m^3/metric ton of product)
COD = Organics loading in wastewater (kg/m^3)
$\%TA_p$ = Percent of wastewater treated anaerobically on site in primary treatment
$\%TA_s$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%Plants_o$ = Percent of plants with onsite treatment
$\%WW_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment
$\%COD_p$ = Percent of COD entering primary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_t$ = Percent of plants with other secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = Percent of COD entering secondary treatment
B_o = Maximum CH_4 producing potential of industrial wastewater (default value of 0.25 kg CH_4/kg COD)
MCF = CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

Alternate methodological equations for calculating %TA were used for secondary treatment in the pulp and paper industry to account for aerobic systems with anaerobic portions. These equations are:

$$\%TA_a = [\%Plants_a \times \%WW_{as} \times \%COD_s]+[\%Plant_{st} \times \%WW_{at} \times COD_s]$$

$$\%TA_{at} = [\%Plants_{at} \times \%WW_{as} \times \%COD_s]$$

where,

$\%TA_a$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%TA_{at}$ = Percent of wastewater treated in aerobic systems with anaerobic portions on site in secondary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_{a,t}$ = Percent of plants with partially anaerobic secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment

$\%COD_s$ = Percent of COD entering secondary treatment

As described below, the values presented in Table 7-13 were used in the emission calculations and are described in detail in ERG (2008), ERG (2013a), and ERG (2013b).

Table 7-13: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (percent)

Variable	Industry						
	Pulp and Paper	Meat Processing	Poultry Processing	Fruit/ Vegetable Processing	Ethanol Production – Wet Mill	Ethanol Production – Dry Mill	Petroleum Refining
$\%TA_p$	0	0	0	0	0	0	0
$\%TA_s$	0	33	25	4.2	33.3	75	23.6
$\%TA_a$	2.2	0	0	0	0	0	0
$\%TA_{a,t}$	11.8	0	0	0	0	0	0
$\%Plants_o$	0	100	100	11	100	100	100
$\%Plants_a$	5	33	25	5.5	33.3	75	23.6
$\%Plants_{a,t}$	28	0	0	0	0	0	0
$\%Plants_t$	35	67	75	5.5	66.7	25	0
$\%WW_{a,p}$	0	0	0	0	0	0	0
$\%WW_{a,s}$	100	100	100	100	100	100	100
$\%WW_{a,t}$	0	0	0	0	0	0	0
$\%COD_p$	100	100	100	100	100	100	100
$\%COD_s$	42	100	100	77	100	100	100

Sources: ERG (2008); ERG (2013a); and ERG (2013b).

Pulp and Paper. Wastewater treatment for the 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. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993). 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 1993). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Based on EPA's OAQPS Pulp and Paper Sector Survey, 5.3 percent of pulp and paper mills reported using anaerobic secondary treatment for wastewater and/or pulp condensates (ERG 2013a). Twenty-eight percent (28 percent) of mills also reported the use of quiescent settling ponds. Using engineering judgment, these systems were determined to be aerobic with possible anaerobic portions. For the truly anaerobic systems, an MCF of 0.8 is used, as these are typically deep stabilization basins. For the partially anaerobic systems, an MCF of 0.2 is used, which is the IPCC suggested MCF for shallow lagoons.

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Data from the Food and Agricultural Organization of the United Nations (FAO) database FAOSTAT were used for 2002 through 2013 (FAO 2014). The overall wastewater outflow varies based on a time series outlined in ERG (2013a) to reflect historical and current industry wastewater flow, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999). The COD:BOD ratio used to convert the organic loading to COD for pulp and paper mills was 2 (EPA 1997a).

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. 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 B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems. Production data, in carcass weight and live weight killed for the meat and poultry industry, were obtained from the USDA Agricultural Statistics Database and the Agricultural Statistics Annual Reports (USDA 2014a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m^3/metric ton for meat and poultry production (live weight killed), respectively (EPA 2002). The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively. The COD:BOD ratio used to convert the organic loading to COD for both meat and poultry facilities was 3 (EPA 1997a).

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. Effluent is suitable for discharge to the sewer. This industry is likely to 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). Consequently, 4.2 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2014a) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 7-14, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors. The COD:BOD ratio used to convert the organic loading to COD for all fruit, vegetable, and juice facilities was 1.5 (EPA 1997a).

Table 7-14: Wastewater Flow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	BOD (g/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	8.67	0.791
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.78	1.831

Sources: 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 only about 2 percent of ethanol production, and although the Department of Energy predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage 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 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 has become more efficient in recent years (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. CH_4 generated in anaerobic digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallons per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling) (Ruocco 2006a,b; Merrick 1998; Donovan 1996; and NRBP 2001). COD concentrations were also found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). The amount of wastewater treated anaerobically was estimated, along with how much of the CH_4 is recovered through the use of biomethanators. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times \%\text{ Not Recovered}] + [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times (\%\text{ Recovered}) \times (1\text{-DE})] \times 1/10\text{^}9$$

where,

Production = gallons ethanol produced (wet milling or dry milling)
Flow = gallons wastewater generated per gallon ethanol produced (1.25 dry milling, 10 wet milling)
COD = COD concentration in influent (3 g/l)
3.785 = conversion, gallons to liters
%Plants$_o$ = percent of plants with onsite treatment (100%)
%WW$_{a,p}$ = percent of wastewater treated anaerobically in primary treatment (0%)
%COD$_p$ = percent of COD entering primary treatment (100%)
%Plants$_a$ = percent of plants with anaerobic secondary treatment (33.3% wet, 75% dry)
%Plants$_t$ = percent of plants with other secondary treatment (66.7% wet, 25% dry)
%WW$_{a,s}$ = percent of wastewater treated anaerobically in anaerobic secondary treatment (100%)
%WW$_{a,t}$ = percent of wastewater treated anaerobically in other secondary treatment (0%)
%COD$_s$ = percent of COD entering secondary treatment (100%)
B_o = maximum methane producing capacity (0.25 g CH_4/g COD)
MCF = methane conversion factor (0.8 for anaerobic systems)
% Recovered = percent of wastewater treated in system with emission recovery
% Not Recovered = 1 - percent of wastewater treated in system with emission recovery
DE = destruction efficiency of recovery system (99%)
1/10^9 = conversion factor, g to kt

A time series of CH_4 emissions for 1990 through 2013 was developed based on production data from the Renewable Fuels Association (RFA 2014).

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.[11] Of the responding facilities, 23.6 percent reported using non-aerated surface impoundments or other biological treatment units, both of which have the potential to lead to anaerobic conditions (ERG 2013b). In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product (ERG 2013b). An average COD value in the wastewater was estimated at 0.45 kg/m^3 (Benyahia et al. 2006).

The equation used to calculate CH_4 generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times \text{TA} \times B_o \times \text{MCF}$$

where,

Flow = Annual flow treated through anaerobic treatment system (m^3/year)
COD = COD loading in wastewater entering anaerobic treatment system (kg/m^3)
TA = Percent of wastewater treated anaerobically on site

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[11] Available online at <https://refineryicr.rti.org/>.

B_o = maximum methane producing potential of industrial wastewater (default value of 0.25 kg CH_4 /kg COD)
MCF = methane conversion factor (0.3)

A time series of CH_4 emissions for 1990 through 2013 was developed based on production data from the Energy Information Association (EIA 2014).

Domestic Wastewater N_2O Emission Estimates

N_2O emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology, including calculations that take into account N removal with sewage sludge, non-consumption and industrial/commercial wastewater N, and emissions from advanced centralized wastewater treatment plants:

- In the United States, a certain amount of N is removed with sewage sludge, which is applied to land, incinerated, or landfilled (N_{SLUDGE}). The N disposal into aquatic environments is reduced to account for the sewage sludge application.
- The IPCC methodology uses annual, per capita protein consumption (kg protein/person-year). For this inventory, the amount of protein available to be consumed is estimated based on per capita annual food availability data and its protein content, and then adjusts that data using a factor to account for the fraction of protein actually consumed.
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 g N_2O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the 2004 CWNS shows that plants with denitrification as one of their unit operations serve a population of 2.4 million people. Based on an emission factor of 7 g per capita per year, approximately 21.2 metric tons of additional N_2O may have been emitted via denitrification in 2004. Similar analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification/denitrification are assumed to generate 3.2 g N_2O per capita per year.

N_2O emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [(US_{POPND}) \times EF_2 \times F_{IND\text{-}COM}] \times 1/10\text{^}9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND}] \times F_{IND\text{-}COM} \times EF_1\} \times 1/10\text{^}9$$

$$N_2O_{EFFLUENT} = \{[(((US_{POP} \times WWTP) - (0.9 \times US_{POPND})) \times Protein \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10\text{^}6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O (kt)
N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (kt)
$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kt)
$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kt)
$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kt)
US_{POP} = U.S. population
US_{POPND} = U.S. population that is served by biological denitrification (from CWNS)
WWTP = Fraction of population using WWTP (as opposed to septic systems)
EF_1 = Emission factor (3.2 g N_2O/person-year) – plant with no intentional denitrification
EF_2 = Emission factor (7 g N_2O/person-year) – plant with intentional denitrification
Protein = Annual per capita protein consumption (kg/person/year)
F_{NPR} = Fraction of N in protein, default = 0.16 (kg N/kg protein)

$F_{NON\text{-}CON}$ = Factor for non-consumed protein added to wastewater (1.4)
$F_{IND\text{-}COM}$ = Factor for industrial and commercial co-discharged protein into the sewer system (1.25)
N_{SLUDGE} = N removed with sludge, kg N/yr
EF_3 = Emission factor (0.005 kg N_2O -N/kg sewage-N produced) – from effluent
0.9 = Amount of nitrogen removed by denitrification systems
44/28 = Molecular weight ratio of N_2O to N_2

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2014) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, and 2011 American Housing Survey (U.S. Census 2011). Data for intervening years were obtained by linear interpolation and data from 2012 and 2013 were forecasted using 1990-2011 data. The emission factor (EF_1) used to estimate emissions from wastewater treatment for plants without intentional denitrification was taken from IPCC (2006), while the emission factor (EF_2) used to estimate emissions from wastewater treatment for plants with intentional denitrification was taken from Scheehle and Doorn (2001). Data on annual per capita protein intake were provided by the U.S. Department of Agriculture Economic Research Service (USDA 2014b). Protein consumption data for 2010 through 2013 were extrapolated from data for 1990 through 2006. An emission factor to estimate emissions from effluent (EF_3) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N_2O-N/kg sewage-N produced) was applied (IPCC 2006). The fraction of N in protein (0.16 kg N/kg protein) was also obtained from IPCC (2006). The factor for non-consumed protein and the factor for industrial and commercial co-discharged protein were obtained from IPCC (2006). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 through 2012 were forecasted from the rest of the time series. The amount of nitrogen removed by denitrification systems was taken from EPA (2008). An estimate for the N removed as sludge (N_{SLUDGE}) was obtained by determining the amount of sludge disposed by incineration, by land application (agriculture or other), through surface disposal, in landfills, or through ocean dumping (US EPA 1993b, Beecher et al. 2007, McFarland 2001, US EPA 1999). In 2013, 286 kt N was removed with sludge. Table 7-15 presents the data for U.S. population, population served by biological denitrification, population served by wastewater treatment plants, available protein, protein consumed, and nitrogen removed with sludge.

Table 7-15: U.S. Population (Millions), Population Served by Biological Denitrification (Millions), Fraction of Population Served by Wastewater Treatment (percent), Available Protein (kg/person-year), Protein Consumed (kg/person-year), and Nitrogen Removed with Sludge (kt-N/year)

Year	Population	$Population_{ND}$	WWTP Population	Available Protein	Protein Consumed	N Removed
1990	253	2.0	75.6	38.4	29.5	214.1
2005	300	2.7	78.8	39.8	30.7	261.1
2009	311	2.9	79.3	40.9	31.5	273.4
2010	313	3.0	80.0	41.0	31.6	276.4
2011	316	3.0	80.6	41.1	31.7	279.5
2012	318	3.0	80.4	41.2	31.8	282.6
2013	320	3.1	80.7	41.3	31.9	285.6

Sources: Beecher et al. 2007, McFarland 2001, U.S. Census 2011, U.S. Census 2014, USDA 2014b, US EPA 1992, US EPA 1993b, US EPA 1996, US EPA 1999, US EPA 2000, US EPA 2004.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2013 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (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 wastewater from pulp and paper manufacture, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N_2O emissions include that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-16. Methane emissions from wastewater treatment were estimated to be between 9.2 and 15.3 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 39 percent below to 2 percent above the 2013 emissions estimate of 15.0 MMT CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be between 1.2 and 10.2 MMT CO_2 Eq., which indicates a range of approximately 76 percent below to 107 percent above the 2013 emissions estimate of 4.9 MMT CO_2 Eq.

Table 7-16: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2013 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**	**15.0**	**9.2**	**15.3**	**-39%**	**+2%**
Domestic	CH_4	9.2	5.7	9.9	-38%	+7%
Industrial	CH_4	5.8	2.4	6.9	-59%	+18%
Wastewater Treatment	**N_2O**	**4.9**	**1.2**	**10.2**	**-76%**	**+107%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed on activity data, documentation, and emission calculations. This effort included a 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 emissions estimates trends; and
- Compared estimates to previous estimates to identify significant changes.

All transcription errors identified were corrected. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Production data were updated to reflect revised USDA NASS datasets. In addition, the most recent USDA ERS data were used to update percent protein values from 1990 through 2010. The updated ERS data also resulted in small changes in forecasted values from 2011. The factor for sewage sludge production change per year was updated to include all available data. This change resulted in updated 1990 through 1995 values for total N in sludge along with a change in forecasted values from 2005 through 2012.

Workbooks were also updated to show emissions in kilotons and MMT CO_2 Eq. In addition, global warming potentials for N_2O and CH_4 were updated with the AR4 100-year values (IPCC 2007).

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Planned Improvements

The methodology to estimate CH_4 emissions from domestic wastewater treatment currently utilizes estimates for the percentage of centrally treated wastewater that is treated by aerobic systems and anaerobic systems. These data come from the 1992, 1996, 2000, and 2004 CWNS. The question of whether activity data for wastewater treatment systems are sufficient across the time series to further differentiate aerobic systems with the potential to generate small amounts of CH_4 (aerobic lagoons) versus other types of aerobic systems, and to differentiate between anaerobic systems to allow for the use of different MCFs for different types of anaerobic treatment systems, continues to be explored. The CWNS data for 2008 were evaluated for incorporation into the Inventory, but due to significant changes in format, this dataset is not sufficiently detailed for inventory calculations. However, additional information and other data continue to be evaluated to update future years of the Inventory, including anaerobic digester data compiled by the North East Biosolids and Residuals Association (NEBRA) in collaboration with several other entities. While NEBRA is no longer involved in the project, the Water Environment Federation (WEF) now hosts and manages the dataset which has been relocated to www.wef.org/biosolids. WEF will complete the second phase of their data collection and by late fall. They are currently collecting additional data on a Region by Region basis which should add to the quality of the database by decreasing uncertainty and data gaps (ERG 2014a). EPA will continue to monitor the status of these data as a potential source of digester, sludge, and biogas data from POTWs.

Data collected under the EPA's Greenhouse Gas Reporting Program Subpart II, Industrial Wastewater Treatment (GHGRP) is being investigated for use in improving the emission estimates for the industrial wastewater category. Ensuring time series consistency has been the focus, as the reporting data from EPA's GHGRP are not available for all inventory years. Whether EPA's GHGRP reporters sufficiently represent U.S. emissions is being investigated to determine if moving to a facility-level implementation of GHGRP data is warranted, or whether the GHGRP data will allow update of activity data for certain industry sectors, such as use of biogas recovery systems or update of waste characterization data. Since EPA's GHGRP only includes reporters that have met a certain threshold and because EPA is unable to review whether the reporters represent the majority of U.S. production, GHGRP data are not believed to be sufficiently representative to move toward facility-level estimates in the Inventory. However, the GHGRP data continues to be evaluated for improvements to activity data, and in verifying methodologies currently in use in the Inventory to estimate emissions (ERG 2014b). In implementing any improvements and integration of data from EPA's GHGRP, EPA will follow the latest guidance from the IPCC on the use of facility-level data in national inventories.[12]

For industrial wastewater emissions, EPA is also working with the National Council of Air and Stream Improvement (NCASI) to determine if there are sufficient data available to update the estimates of organic loading in pulp and paper wastewaters treated on site. These data include the estimates of wastewater generated per unit of production, the BOD and/or COD concentration of these wastewaters, and the industry-level production basis used in the Inventory. EPA has received data on the industry-level production basis to date and intends to incorporate these data once a full evaluation of the production basis is made in relation to the wastewater generation rate and the organic

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[12] See: <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

content of the wastewater. In this way, EPA plans to make a coordinated update to the three values that are used to estimate the total organic industry load to wastewater treatment plants, rather than multiple changes over time.

In addition to this investigation, any reports based on international research will be investigated to inform potential updates to the Inventory. The Global Water Research Coalition report has been evaluated, regarding wastewater collection and treatment systems (GWRC 2011). The report included results of studies from Australia, France, the Netherlands, and the United States. Since each dataset was taken from a variety of wastewater treatment plant types using different methodologies and protocols, it was determined that it was not representative enough to include in the Inventory at this time (ERG 2014a). In addition, wastewater inventory submissions from other countries have been investigated to determine if there are any emission factors, specific methodologies, or additional industries that could be used to inform the U.S. inventory calculations. Although no comparable data have been found, other countries' submissions will continue to be investigated for potential improvements to the inventory.

IPCC's 2013 wetlands supplement has also been investigated regarding the inclusion of constructed and semi-natural treatment wetlands in Inventory calculations (IPCC 2014). Methodologies are presented for estimating both CH_4 and N_2O. Next, the use of CWNS treatment system data will be investigated to determine if these data can be used to estimate the amount of wastewater treated in constructed wetlands for potential implementation in future Inventory reports.

Currently, for domestic wastewater, it is assumed that all aerobic wastewater treatment systems are well managed and produce no CH_4 and that all anaerobic systems have an MCF of 0.8. Efforts to obtain better data reflecting emissions from various types of municipal treatment systems are currently being pursued by researchers, including the Water Environment Research Federation (WERF). This research includes data on emissions from partially anaerobic treatment systems which was reviewed (Willis et al. 2013). It was determined that the emissions were too variable and the sample size too small to include in the Inventory at this time. In addition, information on flare efficiencies was reviewed and it was determined that they were not suitable for use in updating the Inventory because the flares used in the study are likely not comparable to those used at wastewater treatment plants (ERG 2014a). The status of this and similar research will continue to be monitored for potential inclusion in the Inventory in the future.

With respect to estimating N_2O emissions, the default emission factors for indirect N_2O from wastewater effluent and direct N_2O from centralized wastewater treatment facilities have a high uncertainty. Research is being conducted by WERF to measure N_2O emissions from municipal treatment systems and is periodically reviewed for its utility for the Inventory. The Phase I report from WERF on N_2O emissions was recently reviewed and EPA concluded, along with the author, that there were not enough data to create an emission factor for N_2O (Chandran 2012). While the authors suggested a facility-level approach, there are not enough data available to estimate N_2O emissions on a facility-level for the more than 16,000 POTWs in the United States (ERG 2014a). In addition, a literature review has been conducted focused on N_2O emissions from wastewater treatment to determine the state of such research and identify data to develop a country-specific N_2O emission factor or alternate emission factor or method (ERG 2011). Such data will continue to be reviewed as they are available to determine if a country-specific N_2O emission factor can or should be developed, or if alternate emission factors should be used. EPA will also follow up with the authors of any relevant studies, including those from WERF, to determine if there is additional information available on potential methodological revisions.

There is the potential for N_2O emissions associated with on-site industrial wastewater treatment operations; however, the methodology provided in IPCC (2006) only addresses N_2O emissions associated with domestic wastewater treatment. A literature review was initiated to assess other Annex I countries' wastewater inventory submissions for additional data and methodologies that could be used to inform the U.S. wastewater inventory calculations, in particular to determine if any countries have developed industrial wastewater N_2O emission estimates (ERG 2014a). Currently, there are insufficient data to develop a country-specific methodology; however, available data will continue to be reviewed, and will consider if indirect N_2O emissions associated with on-site industrial wastewater treatment using the IPCC default factor for domestic wastewater (0.005 kg N_2O-N/kg N) would be appropriate.

Previously, a new measurement data from WERF was used to develop a U.S.-specific emission factor for CH_4 emissions from septic systems, and these were incorporated into the inventory emissions calculation. Due to the high uncertainty of the measurements for N_2O from septic systems, estimates of N_2O emissions were not included. Appropriate emission factors for septic system N_2O emissions will continue to be investigated as the data collected by WERF indicate that septic soil systems are a source of N_2O emissions.

In addition, the estimate of N entering municipal treatment systems is under review. The factor that accounts for non-sewage N in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Obtaining data on the changes in average influent N concentrations to centralized treatment systems over the time series would improve the estimate of total N entering the system, which would reduce or eliminate the need for other factors for non-consumed protein or industrial flow. The dataset previously provided by the National Association of Clean Water Agencies (NACWA) was reviewed to determine if it was representative of the larger population of centralized treatment plants for potential inclusion into the Inventory. However, this limited dataset was not representative of the number of systems by state or the service populations served in the United States, and therefore could not be incorporated into the inventory methodology. Additional data sources will continue to be researched with the goal of improving the uncertainty of the estimate of N entering municipal treatment systems. Unfortunately, NACWA's suggestion of using National Pollution Discharge Elimination System (NPDES) permit data to estimate nitrogen loading rates is not feasible as influent concentration are not available. EPA is also evaluating whether available effluent nitrogen concentrations reported under POTW NPDES permits would support a more robust analysis of nitrogen contributing to indirect nitrous oxide emissions. Not every POTW is required to measure for effluent nitrogen so the database is not a complete source. Often, only those POTWs that are required to reduce nutrients are monitoring effluent nitrogen, so the database may reflect lower N effluent loadings than that typical throughout the United States. However, EPA is continuing to evaluate the utility of these data in future inventories.

The value used for N content of sludge continues to be investigated. This value is driving the N_2O emissions for wastewater treatment and is static over the time series. To date, new data have not been identified that would be able to establish a time series for this value. The amount of sludge produced and sludge disposal practices will also be investigated. In addition, based on UNFCCC review comments, the transparency of the fate of sludge produced in wastewater treatment will continue to be improved.

A review of other industrial wastewater treatment sources for those industries believed to discharge significant loads of BOD and COD has been ongoing. Food processing industries have the highest potential for CH_4 generation due to the waste characteristics generated, and the greater likelihood to treat the wastes anaerobically. However, in all cases there is dated information available on U.S. wastewater treatment operations for these industries. Previously, organic chemicals, the seafood processing industry, and coffee processing were investigated to estimate their potential to generate CH_4. Due to the insignificant amount of CH_4 estimated to be emitted and the lack of reliable, up-to-date activity data, these industries were not selected for inclusion in the Inventory. Analyses of breweries and dairy products processing facilities have been performed. While the amount of COD present in brewery wastewater is substantial, it is likely that the majority of the industry utilizes aerobic treatment or anaerobic treatment with biogas recovery. As a result, breweries will not be included in the Inventory at this time. There are currently limited data available on the wastewater characteristics and treatment of dairy processing wastewater, but EPA will continue to investigate this and other industries as necessary for inclusion in future years of the Inventory.

7.3 Composting (IPCC Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and sludge, is common in the United States. Advantages of composting include reduced volume in the waste, stabilization of the waste, and destruction of pathogens in the waste. The end products of composting, depending on its quality, can be recycled as fertilizer and soil amendment, or be disposed in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide (CO_2). Methane (CH_4) is formed in anaerobic sections of the compost, which are created when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. This CH_4 is then oxidized to a large extent in the aerobic sections of the compost. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NOx) denitrification during the later composting stages. 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 2013, the amount of waste composted in the United States has increased from 3,810 kt to 19,633 kt, an increase of approximately 415 percent. From 2000 to 2013, the amount of material composted in the United States has increased by approximately 32 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage. In 2013, CH_4 emissions from composting (see Table 7-17 and Table 7-18) were 2.0 MMT CO_2 Eq. (79 kt), and N_2O emissions from composting were 1.8 MMT CO_2 Eq. (6 kt). The wastes composted primarily include yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from residences and commercial establishments (such as grocery stores, restaurants, and school and factory cafeterias). The composted waste quantities reported here do not include backyard composting. The growth in composting since the 1990s is attributable to primarily two factors: (1) steady growth in population and residential housing, and (2) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills. Most bans on disposal of yard trimmings initiated in the early 1990’s (US Composting Council 2010). By 2010, 25 states, representing about 50 percent of the nation’s population, had enacted such legislation (BioCycle 2010). An additional 16 states are known to have commercial-scale composting facilities (Shin 2014). Despite these factors, the total amount of waste composted exhibited a downward trend after peaking in 2008 (see Table 7-17). The amount of waste composted has been increasing slightly since 2010 however.

Table 7-17: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2009	2010	2011	2012	2013
CH_4	0.4	1.9	1.9	1.8	1.9	1.9	2.0
N_2O	0.3	1.7	1.7	1.6	1.7	1.7	1.8
Total	**0.7**	**3.6**	**3.6**	**3.5**	**3.5**	**3.7**	**3.7**

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Table 7-18: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2009	2010	2011	2012	2013
CH_4	15	75	75	73	75	77	79
N_2O	1	6	6	5	6	6	6

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 and aeration during the process.

The emissions shown in Table 7-17 and Table 7-18 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is 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):

$$E_i = M \times EF_i$$

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), and
i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 7-19. Estimates of the quantity composted for 1990, 2005 and 2007 through 2009 were taken from *Municipal Solid Waste in the United States: 2010 Facts and Figures* (EPA 2011); estimates of the quantity composted for 2006 were taken from EPA’s *Municipal Solid Waste In The United States: 2006 Facts and Figures* (EPA 2007); estimates of the quantity composted for 2011 through 2013 were taken from EPA’s *Municipal Solid Waste In The United States: 2012 Facts and Figures* (EPA 2014);

estimates of the quantity composted for 2013 were calculated using the 2012 quantity composted and a ratio of the U.S. population in 2012 and 2013 (U.S. Census Bureau 2014).

Table 7-19: U.S. Waste Composted (kt)

Activity	1990		2005		2009	2010	2011	2012	2013
Waste Composted	3,810		18,643		18,824	18,298	18,661	19,351	19,633

Uncertainty and Time-Series Consistency

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Approach 1 methodology. Emissions from composting in 2013 were estimated to be between 1.9 and 5.6 MMT CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2013 emission estimate of 3.7 MMT CO_2 Eq. (see Table 7-20).

Table 7-20: Approach 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2013 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4, N_2O	3.7	1.9	5.6	-50%	+50%

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. A primary focus of the QA/QC checks was to ensure that the amount of waste composted annually was correct according to the latest EPA *Municipal Solid Waste In The United States: Facts and Figures* report.

Recalculations Discussion

The estimated amount of waste composted in 2010 through 2012 was updated based on new data contained in EPA's *Municipal Solid Waste In The United States: 2012 Facts and Figures* (EPA 2014). The amounts of CH_4 and N_2O emissions estimates presented in Table 7-17 and Table 7-18 were revised accordingly.

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). AR4 GWP values differ slightly from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) (used in the previous inventories) which results in time-series recalculations for most inventory sources. Under the most recent reporting guidelines (UNFCCC 2014), countries are required to report using the AR4 GWPs, which reflect an updated understanding of the atmospheric properties of each greenhouse gas. The GWPs of CH_4 and most fluorinated greenhouse gases have increased, leading to an overall increase in CO_2-equivalent emissions from CH_4. The GWPs of N_2O and SF_6 have decreased, leading to a decrease in CO_2-equivalent emissions for N_2O. The AR4 GWPs have been applied across the entire time series for consistency. For more information please see the Recalculations and Improvements Chapter.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH_4 and N_2O emissions from composting. For example, a literature search may be conducted to determine if emission factors specific to various composting systems and composted materials are available. Further cooperation with estimating emissions in cooperation with the LULUCF Other section will be made.

7.4 Waste Incineration (IPCC Source Category 5C1)

As stated earlier in this chapter, CO_2, N_2O, and CH_4 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 2013 resulted in 10.4 MMT CO_2 Eq. emissions, over half of which (5.7 MMT CO_2 Eq.) is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration 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 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 UNFCCC. More information on this analysis is provided in Annex 5.

7.5 Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2013 are provided in Table 7-21.

Table 7-21: Emissions of NO_x, CO, and NMVOC from Waste (kt)

Gas/Source	1990	2005	2009	2010	2011	2012	2013
NO_x	**1**	**3**	**2**	**2**	**1**	**1**	**1**
Landfills	+	3	2	2	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous[a]	+	0	0	0	0	0	0
CO	**1**	**7**	**6**	**5**	**5**	**5**	**5**
Landfills	1	7	6	5	5	5	5
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	0	0	0	0	0	0
NMVOCs	**742**	**126**	**54**	**48**	**42**	**42**	**42**
Wastewater Treatment	63	54	23	21	18	18	18
Miscellaneous[a]	614	48	20	18	16	16	16
Landfills	64	24	10	9	8	8	8

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

Methodology

Emission estimates for 1990 through 2013 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Emission estimates for 2013 for non-EGU and non-mobile sources are held constant from 2011 in EPA (2015). Emission estimates of these gases were provided by sector, using a “top down” estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2013. Details on the emission trends through time are described in more detail in the Methodology section, above.

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, emission and sink estimates are recalculated and revised for all years in the Inventory of U.S. Greenhouse Gas Emissions and Sinks, as attempts are made to improve both the analyses themselves, through the use of better methods or data, and the overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "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; new inventory methods become available; and for correction of errors."

The results of all methodological changes and historical data updates made in the current Inventory report are presented in this section; detailed descriptions of each recalculation are contained within each source's description found in this report, if applicable. Table 9-2 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and sinks and Table 9-3 summarizes the quantitative effect on annual net CO_2 fluxes, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2012 report). These tables present the magnitude of these changes in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).

The Recalculations Discussion section of each source's description in the respective chapter of this Inventory presents the details of each recalculation. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 2012) has been recalculated to reflect the change, per IPCC (2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies.

For the current Inventory, emission estimates have been revised to reflect the GWPs provided in the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). Revised UNFCCC reporting guidelines for national inventories now require the use of GWP values from AR4 (IPCC 2007),[298] which reflect an updated understanding of the atmospheric properties of each greenhouse gas. AR4 GWP values differ from those presented in the *IPCC Second Assessment Report* (SAR) (IPCC 1996) and used in the previous inventories as required by earlier UNFCCC reporting guidelines. The use of AR4 GWP values in this Inventory results in time-series recalculations for most inventory sources. In Table 9-1 below, recalculations are presented including both the quantitative effect of the data and methodological changes as well as the quantitative effect of the change in using the AR4 GWP.

The following ten emission sources and sinks, which are listed in absolute decending order of the average change in emissions or sequestration between 1990 and 2012, underwent some of the most significant methodological and historical data changes. These emission sources consider only methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken is provided for each of the ten sources.

- *Forest Land Remaining Forest Land (CO_2 sink).* Forest ecosystem stock and stock-change estimates differ from the previous Inventory (EPA 2014) principally due to some changes in data and methods. The net effect of the modifications was to slightly reduce net C uptake (i.e., lower sequestration) and C stocks from 1990 to the present. The estimate of net annual change in HWP C stock and total C stock in HWP were revised upward by small amounts. The increase in total net annual additions compared to estimates published in 2013 was 2 to 3

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[298] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

percent for 2010 through 2012. This increase was mostly due to changes in the amount of pulpwood used for paper and composite panel products back to 2003. All the adjustments were made as a result of corrections in the database of forest products statistics used to prepare the estimates (Howard forthcoming). These changes resulted in an average annual increase of 76.7 MMT CO_2 Eq. relative to the previous Inventory.

- *Agricultural Soil Management (N_2O).* Methodological recalculations in the current Inventory were associated with the following improvements: 1) Driving the DAYCENT simulations with updated input data for the excretion of C and N onto PRP and N additions from managed manure based on national livestock population (note that revised total PRP N additions decreased from 4.4 to 4.1 MMT N on average and revised managed manure additions decreased from 2.9 to 2.7 MMT N on average); 2) properly accounting for N inputs from residues for crops not simulated by DAYCENT; (3) modifying the number of experimental study sites used to quantify model uncertainty for direct N_2O emissions and bias correction; and (4) reporting indirect N_2O emissions from forestland and settlements in their respective sections, instead of the agricultural soil management section. These changes resulted in an average annual decrease of 43.6 MMT CO_2 Eq. relative to the previous Inventory.

- *Petrochemical Production (CO_2).* Emission information from EPA's GHGRP was used to update estimates. Average country-specific CO_2 emission factors were derived from the 2010 through 2013 GHGRP data for carbon black, ethylene, ethylene dichloride, and ethylene oxide. Annual production and CO_2 emission factor data were obtained from EPA's GHGRP for 2010 through 2013, and were used to estimate emissions for 2010 through 2013. An average CO_2 emission factor was calculated from the 2010 through 2013 GHGRP data and was used to estimate emissions for 1990 through 2009 for carbon black, ethylene, ethylene dichloride, and ethylene oxide using historic production data compiled for 1990 through 2009 (ACC 2014a; ACC 2014b). Note, ethylene oxide is included in the IPCC petrochemical production source category but had not been included in previous versions of this Inventory due to lack of publicly-available data. Similarly, acrylonitrile is included in the IPCC Petrochemical Production source category but had not been included in the previous Inventory due to lack of publicly-available data. Annual acrylonitrile production data for 1990 through 2013 was obtained from ACC (ACC 2014b). These changes resulted in an average annual increase of 23.5 MMT CO_2 Eq. relative to the previous Inventory.

- *Landfills (CH_4).* Three major methodological recalculations were performed for the current Inventory. First, a new SOG survey was published allowing for the update of the annual quantities of waste generated and disposed and the amount of CH_4 generated for the years 2009 through 2012. Second, the percent of the U.S. population within the three precipitation ranges were updated for the year 2010 (see Table A-3 in Annex 3.14), which impacted the distribution for the years 2001 through 2013 in the waste model. Third, the EPA's GHGRP CH_4 recovery and destruction efficiency data were incorporated. These changes resulted in an average annual increase of 18.9 MMT CO_2 Eq. relative to the previous Inventory.

- *Petroleum Systems (CH_4).* For the current Inventory, EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories' formal public notice periods, the latest GHGRP data, and new studies. EPA carefully evaluated relevant information available, and made several updates, such as updates to offshore platforms, pneumatic controllers, refineries, and well count data. In addition, revisions to use the latest activity data resulted in changes to emissions for several sources. The decrease in calculated emissions from this source is largely due to the recalculation for offshore platforms.

  The net impact of the changes (comparing 2012 estimate from previous (2014) Inventory and current (2015) Inventory) is a decrease in CH_4 emissions of around 14.5 MMT CO_2 Eq., or 38 percent. Recalculations in the offshore petroleum platforms estimates resulted in a large decrease in the 2012 CH_4 emission estimate from this source in the production segment, from 15.2 MMT CO_2 Eq. in the previous (2014) Inventory, to 4.7 MMT CO_2 Eq. in the current (2015) Inventory. Recalculations to the onshore petroleum production emissions estimates resulted in a small decrease in the 2012 CH_4 emission estimate for onshore sources, from 22.0 MMT CO_2 Eq. in the 2014 Inventory, to 19.5 MMT CO_2 Eq. in the 2015 Inventory. Methane emission estimates for other segments (i.e., refining and transport) changed by around 0.5 percent.

Across the 1990 through 2012 time series, compared to the previous (2014) Inventory, in the current (2015) Inventory, the CH_4 emission estimate decreased by 11.8 MMT CO_2 Eq. on average.[299]

- *Fossil Fuel Combustion (CO_2)* The Energy Information Administration (EIA 2015) updated energy consumption statistics across the time series relative to the previous Inventory. One such revision is the historical petroleum consumption in the residential sector in 2011 and 2012. These revisions primarily impacted the previous emission estimates from 2010 to 2012; however, additional revisions to industrial and transportation petroleum consumption as well as industrial natural gas and coal consumption impacted emission estimates across the time series. In addition, EIA revised the heat contents of motor gasoline, distillate fuel, and petroleum coke.

  For motor gasoline, heating values were previously based on the relative volumes of conventional and reformulated gasoline in the total motor gasoline product supplied to the United States. The revised heating values (first occurring in the January 2015 publication of the Monthly Energy Review) incorporated inputs of ethanol, methyl tert-butyl ether (MTBE) through April 2006, other oxygenates through 2006, and a single national hydrocarbon gasoline blend-stock from 1993 through 2013.

  Changes to the heat content of distillate fuel resulted in an annual average decrease of approximately 0.1 percent between 1994 through 2012. This decrease was a result of EIA's heat content revision from a constant sulfur content across the time series, to a weighted sulfur content. Additionally, in 2009, EIA began subtracting inputs of renewable diesel fuel from petroleum consumption before converting to energy units.

  Petroleum coke consumption decreased by an annual average of approximately 0.1 percent from 2004 to 2012. This decrease was a result of a similar heat content revision in which the EIA recalculated the historically constant petroleum coke heat content to include weighted petroleum coke heat contents (by the two categories of petroleum coke, catalyst and marketable) starting in 2004.

  Overall, these changes resulted in an average annual decrease of 9.6 MMT CO_2 Eq. (less than 0.2 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2012, relative to the previous report.

- *Nitric Acid Production (N_2O).* GHGRP data from subpart V of regulation 40 CFR Part 98 were used to recalculate emissions from nitric acid production over the entire time series (EPA 2014), and used directly for emission estimates for 2010 through 2013. Nitric acid production and N_2O emissions data were available for 2010 through 2013 from EPA's GHGRP, given nearly all nitric acid production facilities, with the exception of the strong acid facility, in the United States are required to report annual data under subpart V. Country-specific N_2O emission factors were developed using the 2010 GHGRP emissions and production data for nitric acid production with abatement and without abatement. Due to differences in operational efficiencies and recent installation of abatement technology at some U.S. facilities, 2010 GHGRP production data were used for recalculating time series emissions (1990 through 2009) instead of average factors developed from 2010 through 2013 GHGRP data. As per the 2010 GHGRP data, 70.7 percent of total domestic nitric acid production was estimated to be produced without any abatement.

  Time series emissions for 1990 through 2009 were recalculated, and the revised emission estimates are approximately 30 percent lower than the prior estimates. Throughout the whole time series, these changes resulted in an average annual decrease of 5.3 MMT CO_2 Eq. relative to the previous Inventory.

- *Natural Gas Systems (CH_4).* For the current Inventory, EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories' formal public notice periods, GHGRP data, and new studies. EPA carefully evaluated relevant information available, and made several updates, including revisions to offshore platforms, pneumatic controllers, well counts data, and hydraulically fractured gas well completions and workovers.

  In addition, revisions to activity data resulted in changes to emission estimates for several sources. For example, the 2014 Inventory used 2011 data as a proxy for condensate production for 2012. The 2015 Inventory was

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[299] Additional information on recent changes to the Inventory can be found at: <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

updated to use the most recent data on condensate production. Large increases in production in the Rocky Mountain and Gulf Coast regions resulted in an increase in calculated 2012 CH_4 emissions from condensate tanks of 0.6 MMT CO_2 Eq., or 15 percent.

The combined impact of all revisions on 2012 natural gas production segment emissions compared to the previous (2014) Inventory, is a decrease in CH_4 emissions of approximately 0.2 MMT CO_2 Eq. Recalculations in the offshore gas platforms estimates resulted in a large decrease in the 2012 CH_4 emission estimate from this source in the production segment, from 7.2 MMT CO_2 Eq. in the previous (2014) Inventory, to 3.8 MMT CO_2 Eq. in the current (2015) Inventory. Recalculations to the onshore gas production emissions estimates resulted in an increase in the 2012 CH_4 emission estimate for onshore sources, from 42.6 MMT CO_2 Eq. in the previous (2014) Inventory, to 46.0 MMT CO_2 Eq. in the current (2015) Inventory. Methane emission estimates for other segments (i.e. processing, transmission and storage, and distribution) changed by less than 0.5 percent.

Across the 1990-2012 time series, compared to the previous (2014) Inventory, in the current (2015) Inventory, the total CH_4 emission estimate decreased by 5.2 MMT CO_2 Eq. on average (or 3 percent), with the largest decreases in the estimate occurring in early years of the time series.[300]

- *Petroleum Systems (CO_2).* EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories' formal public notice periods, the latest GHGRP data, and new studies. EPA carefully evaluated relevant information available, and made several updates, such as updates to offshore platforms, pneumatic controllers, refineries, and well count data. In addition, revisions to use the latest activity data resulted in changes to emissions for several sources.

  The net impact of the changes (comparing 2012 estimate from previous (2014) Inventory and current (2015) Inventory) is an increase in CO_2 emissions of around 6 MMT CO_2, or 1,400 percent. The increase in the CO_2 emission estimates is due to the update to the petroleum refineries calculations.

  Across the 1990-2012 time series, compared to the previous (2014) Inventory, in the current (2015) Inventory, the CO_2 emissions estimate increased by 4.4 MMT CO_2 Eq. on average (or around 1,300 percent).[301]

- *Cropland Remaining Cropland (CO_2 sink).* Recalculations for the cropland remaining cropland source is divided up into three components: Refining parameters associated with simulating crop production and carbon inputs to the soil in the DAYCENT biogeochemical model; improving the model simulation of snow melt and water infiltration in soils; and driving the DAYCENT simulations with updated input data for managed manure based on national livestock population. These changes resulted in an average annual decrease of 4.3 MMT CO_2 Eq. relative to the previous Inventory.

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[300] Additional information on recent changes to the Inventory can be found at: <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html.>

[301] Additional information on recent changes to the Inventory can be found at: http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html.

Table 9-1: Revisions to U.S. Greenhouse Gas Emissions, Including Quantitative Change Related to Use of AR4 GWP values (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	Average Annual Change
CO_2	**15.0**	**21.7**	**(5.5)**	**(17.8)**	**(23.3)**	**(24.9)**	**15.3**
Fossil Fuel Combustion	(4.4)	(5.2)	(28.7)	(37.8)	(39.8)	(46.3)	(9.6)
Electricity Generation	NC	(1.3)	(0.8)	(0.8)	(0.8)	(0.5)	(0.4)
Transportation	(0.2)	(3.9)	(27.4)	(33.1)	(36.3)	(38.8)	(8.2)
Industrial	(2.6)	0.2	0.2	0.1	5.4	10.1	0.5
Residential	NC	(0.1)	+	(0.1)	2.3	(5.8)	(0.1)
Commercial	(1.6)	(0.1)	(0.4)	(0.5)	(0.5)	(0.3)	(0.3)
U.S. Territories	NC	+	(0.3)	(3.4)	(9.8)	(11.0)	(1.1)
Non-Energy Use of Fuels	(3.2)	(2.1)	(2.1)	(6.3)	(9.0)	(5.4)	(3.2)
Natural Gas Systems	(0.1)	+	+	+	0.5	(0.5)	+
Cement Production	NC	NC	NC	NC	NC	NC	NC
Lime Production	0.3	0.6	0.5	0.5	0.5	0.4	0.5
Other Process Uses of Carbonates	NC	NC	NC	NC	NC	+	+
Glass Production	NC	NC	NC	NC	NC	+	+
Soda Ash Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	0.1	0.1	+	(1.0)	(1.0)	(1.0)	(0.1)
Incineration of Waste	NC	NC	(0.4)	(1.0)	(1.6)	(1.8)	(0.2)
Titanium Dioxide Production	NC	NC	NC	NC	NC	(0.2)	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	+	+
Ferroalloy Production	NC	NC	NC	NC	0.1	0.2	+
Ammonia Production	NC	NC	NC	NC	(0.1)	+	+
Urea Consumption for Non-Agricultural Purposes	NC	NC	+	+	+	(0.8)	+
Phosphoric Acid Production	+	+	+	+	+	+	+
Petrochemical Production	18.2	23.8	20.9	23.9	22.9	23.0	23.5
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Lead Production	NC	NC	NC	NC	NC	NC	NC
Zinc Production	NC	NC	NC	NC	+	0.1	+
Liming of Agricultural Soils	NC	NC	NC	NC	NC	1.8	0.1
Peatlands Remaining Peatlands	+	+	(0.1)	+	+	+	+
Petroleum Systems	4.1	4.6	4.3	3.8	4.1	4.7	4.4
Magnesium Production and Processing	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Urea Fertilization	NC	NC	NC	+	0.1	0.8	+
Land Use, Land-Use Change, and Forestry (Sink)[a]	*55.3*	*118.8*	*90.7*	*96.4*	*99.3*	*98.9*	*72.2*
Biomass – Wood[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*0.9*	*+*
International Bunker Fuels[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
Biomass – Ethanol[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
CH_4	**109.8**	**122.1**	**113.0**	**81.6**	**82.6**	**80.4**	**111.7**
Stationary Combustion	1.0	0.8	0.7	0.7	0.7	0.9	0.9
Mobile Combustion	1.1	0.6	0.5	0.5	0.5	0.5	0.8
Coal Mining	15.4	10.5	12.8	13.2	11.4	10.6	11.9
Abandoned Underground Coal Mines	1.2	1.1	1.2	1.6	1.6	1.5	1.3
Natural Gas Systems	22.7	24.3	25.1	24.9	26.1	24.5	23.9
Petroleum Systems	(4.2)	(5.4)	(7.6)	(8.2)	(8.6)	(8.5)	(5.8)
Petrochemical Production	(2.0)	(3.0)	(2.8)	(3.0)	(3.1)	(3.0)	(2.8)
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	0.2	0.1	0.1	0.1	0.1	0.1	0.2
Ferroalloy Production	+	+	+	+	+	+	+

Enteric Fermentation	26.3	26.4	26.6	26.2	25.8	25.3	26.7
Manure Management	5.7	8.8	9.2	9.1	9.4	10.8	7.9
Rice Cultivation	1.5	1.4	1.5	1.8	1.4	1.9	1.5
Field Burning of Agricultural Residues	0.1	+	+	+	+	+	+
Forest Fires	+	0.2	0.1	+	0.6	0.4	0.2
Peatlands Remaining Peatlands	NC	NC	NC	NC	NC	NC	NC
Landfills	38.5	53.4	42.8	11.9	13.9	12.4	42.2
Wastewater Treatment	2.5	2.5	2.5	2.5	2.4	2.4	2.6
Composting	0.1	0.3	0.3	0.3	0.3	0.3	0.2
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[a]	+	+	+	+	+	+	+
N_2O	**(68.7)**	**(59.9)**	**(56.1)**	**(49.3)**	**(45.3)**	**(44.5)**	**(63.4)**
Stationary Combustion	(0.3)	(0.4)	(0.3)	(0.4)	(0.3)	(0.6)	(0.4)
Mobile Combustion	(2.8)	1.2	1.9	3.0	4.0	3.7	(0.4)
Adipic Acid Production	(0.6)	(0.3)	(0.1)	(0.2)	(0.4)	(0.2)	(0.3)
Nitric Acid Production	(6.0)	(5.6)	(4.4)	(5.2)	(5.0)	(4.8)	(6.0)
Manure Management	(0.6)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.6)
Agricultural Soil Management	(58.1)	(53.7)	(52.3)	(45.8)	(42.0)	(40.6)	(55.2)
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)
N_2O from Product Uses	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Incineration of Waste	+	+	+	+	(0.1)	(0.1)	+
Settlement Soils	0.4	0.9	0.8	0.9	1.0	1.1	0.8
Forest Fires	(0.4)	(1.1)	(0.9)	(0.7)	(1.8)	(2.1)	(1.0)
Forest Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Composting	+	(0.1)	(0.1)	(0.1)	(0.1)	+	+
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Semiconductor Manufacture	NC*	NC*	NC*	NC*	NC*	NC*	NC*
International Bunker Fuels[a]	+	+	+	+	+	+	+
HFCs	**9.7**	**11.6**	**7.8**	**8.6**	**8.8**	**8.0**	**11.9**
Substitution of Ozone Depleting Substances	+	7.3	6.4	6.9	6.9	6.8	5.9
HCFC-22 Production	9.7	4.2	1.4	1.7	1.8	1.1	6.0
Semiconductor Manufacture	+	+	+	+	+	+	0.1
Magnesium Production and Processing	NC*	NC*	NC*	NC*	NC*	NC*	NC*
PFCs	**3.6**	**1.1**	**0.6**	**0.7**	**0.9**	**0.6**	**2.0**
Aluminum Production	3.0	0.5	0.3	0.3	0.5	0.4	1.2
Semiconductor Manufacture	0.6	0.6	0.3	0.4	0.4	0.1	0.8
SF_6	**(1.6)**	**(0.6)**	**(0.3)**	**(0.3)**	**(0.8)**	**(0.7)**	**(0.9)**
Electrical Transmission and Distribution	(1.3)	(0.5)	(0.2)	(0.2)	(0.4)	(0.3)	(0.7)
Semiconductor Manufacture	+	+	+	+	(0.3)	(0.3)	(0.1)
Magnesium Production and Processing	(0.3)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)
NF_3	**NC***	**NC***	**NC***	**NC***	**NC***	**NC***	**NC***
Semiconductor Manufacture	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Net Change in Total Emissions[b]	**67.8**	**96.4**	**59.9**	**24.1**	**23.6**	**19.5**	
Percent Change	**1.1%**	**1.3%**	**0.9%**	**0.4%**	**0.4%**	**0.3%**	

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

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

[a] Not included in emissions total.

[b] Excludes net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from International Bunker Fuels.

Table 9-2: Revisions to U.S. Greenhouse Gas Emissions due only to Methodology and Data Changes, with the AR4 GWP values applied across the time series (MMT CO_2 Eq.)

Gas/Source	1990	2005	2009	2010	2011	2012	Average Annual Change
CO_2	**15.0**	**21.7**	**(5.5)**	**(17.8)**	**(23.3)**	**(24.9)**	**15.3**
Fossil Fuel Combustion	(4.4)	(5.2)	(28.7)	(37.8)	(39.8)	(46.3)	(9.6)
Electricity Generation	NC	(1.3)	(0.8)	(0.8)	(0.8)	(0.5)	(0.4)
Transportation	(0.2)	(3.9)	(27.4)	(33.1)	(36.3)	(38.8)	(8.2)
Industrial	(2.6)	0.2	0.2	0.1	5.4	10.1	0.5
Residential	NC	(0.1)	+	(0.1)	2.3	(5.8)	(0.1)
Commercial	(1.6)	(0.1)	(0.4)	(0.5)	(0.5)	(0.3)	(0.3)
U.S. Territories	NC	+	(0.3)	(3.4)	(9.8)	(11.0)	(1.1)
Non-Energy Use of Fuels	(3.2)	(2.1)	(2.1)	(6.3)	(9.0)	(5.4)	(3.2)
Natural Gas Systems	(0.1)	+	+	+	0.5	(0.5)	+
Cement Production	NC	NC	NC	NC	NC	NC	NC
Lime Production	0.3	0.6	0.5	0.5	0.5	0.4	0.5
Other Process Uses of Carbonates	NC	NC	NC	NC	NC	+	+
Glass Production	NC	NC	NC	NC	NC	+	+
Soda Ash Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	0.1	0.1	+	(1.0)	(1.0)	(1.0)	(0.1)
Incineration of Waste	NC	NC	(0.4)	(1.0)	(1.6)	(1.8)	(0.2)
Titanium Dioxide Production	NC	NC	NC	NC	NC	(0.2)	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	+	+
Ferroalloy Production	NC	NC	NC	NC	0.1	0.2	+
Ammonia Production	NC	NC	NC	NC	(0.1)	+	+
Urea Consumption for Non-Agricultural Purposes	NC	NC	+	+	+	(0.8)	+
Phosphoric Acid Production	+	+	+	+	+	+	+
Petrochemical Production	18.2	23.8	20.9	23.9	22.9	23.0	23.5
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Lead Production	NC	NC	NC	NC	NC	NC	NC
Zinc Production	NC	NC	NC	NC	+	0.1	+
Liming of Agricultural Soils	NC	NC	NC	NC	NC	1.8	0.1
Peatlands Remaining Peatlands	+	+	(0.1)	+	+	+	+
Petroleum Systems	4.1	4.6	4.3	3.8	4.1	4.7	4.4
Magnesium Production and Processing	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Urea Fertilization	NC	NC	NC	+	0.1	0.8	+
Land Use, Land-Use Change, and Forestry (Sink)[a]	*55.3*	*118.8*	*90.7*	*96.4*	*99.3*	*98.9*	*NC*
Biomass – Wood[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*0.9*	*+*
International Bunker Fuels[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
Biomass – Ethanol[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
CH_4	**(11.3)**	**10.5**	**(0.7)**	**(29.9)**	**(27.5)**	**(27.7)**	**(3.7)**
Stationary Combustion	(0.4)	(0.5)	(0.5)	(0.5)	(0.5)	(0.2)	(0.4)
Mobile Combustion	0.2	0.2	0.1	0.2	0.2	0.2	0.2
Coal Mining	NC	0.3	NC	NC	NC	NC	+
Abandoned Underground Coal Mines	NC	NC	0.3	0.6	0.7	0.6	0.1
Natural Gas Systems	(7.1)	(4.7)	(2.1)	(0.8)	0.7	(0.2)	(5.2)
Petroleum Systems	(11.1)	(10.9)	(13.2)	(13.8)	(14.4)	(14.5)	(11.8)
Petrochemical Production	(2.5)	(3.6)	(3.4)	(3.6)	(3.7)	(3.6)	(3.4)
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	NC	NC
Ferroalloy Production	NC	NC	NC	NC	+	+	+

Enteric Fermentation	NC	(0.7)	(1.2)	(1.4)	(1.5)	(1.5)	(0.7)
Manure Management	(0.3)	(0.3)	(0.4)	(0.7)	(0.5)	0.7	(0.3)
Rice Cultivation	NC	NC	NC	NC	NC	0.5	+
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	NC
Forest Fires	(0.5)	(1.4)	(1.0)	(0.9)	(2.0)	(2.5)	(1.2)
Peatlands Remaining Peatlands	NC	NC	NC	NC	NC	NC	NC
Landfills	10.3	32.0	20.8	(9.0)	(6.5)	(7.2)	18.9
Wastewater Treatment	+	+	+	+	+	+	+
Composting	NC	NC	NC	NC	+	+	+
Incineration of Waste	NC	NC	+	+	+	+	+
International Bunker Fuels[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
N_2O	**(53.3)**	**(43.8)**	**(40.2)**	**(33.4)**	**(29.2)**	**(28.6)**	**(47.1)**
Stationary Combustion	0.1	0.4	0.5	0.5	0.5	0.2	0.3
Mobile Combustion	(1.1)	2.6	2.8	3.8	4.7	4.3	1.2
Adipic Acid Production	NC	NC	NC	NC	NC	+	+
Nitric Acid Production	(5.3)	(5.0)	(3.8)	(4.5)	(4.3)	(4.2)	(5.3)
Manure Management	NC	NC	+	+	+	+	+
Agricultural Soil Management	(47.2)	(42.2)	(40.0)	(33.8)	(30.0)	(28.8)	(43.6)
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	NC
Wastewater Treatment	+	+	+	+	+	+	+
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	+	+	+	+	+
Settlement Soils	0.4	0.9	0.9	0.9	1.0	1.1	0.8
Forest Fires	(0.3)	(0.9)	(0.7)	(0.6)	(1.3)	(1.7)	(0.8)
Forest Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Composting	NC	NC	NC	NC	+	+	+
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Semiconductor Manufacture	NC*	NC*	NC*	NC*	NC*	NC*	NC*
International Bunker Fuels[a]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
HFCs	**+**	**(1.6)**	**(5.5)**	**(6.3)**	**(7.1)**	**(8.3)**	**(0.9)**
Substitution of Ozone Depleting Substances	+	(1.6)	(5.5)	(6.3)	(7.1)	(8.3)	(0.9)
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	+	+	+	+	+	+
Magnesium Production and Processing	NC*	NC*	NC*	NC*	NC*	NC*	NC*
PFCs	**+**	**(0.5)**	**(0.5)**	**(0.5)**	**(0.7)**	**(0.9)**	**(0.3)**
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	+	(0.5)	(0.5)	(0.5)	(0.7)	(0.9)	(0.3)
SF_6	**(0.1)**	**+**	**0.1**	**0.1**	**(0.3)**	**(0.3)**	**+**
Electrical Transmission and Distribution	(0.1)	+	0.2	0.1	+	+	+
Semiconductor Manufacture	NC	+	+	+	(0.2)	(0.2)	+
Magnesium Production and Processing	NC	NC	+	+	+	+	+
NF_3	**NC***	**NC***	**NC***	**NC***	**NC***	**NC***	**NC***
Semiconductor Manufacture	**NC***	**NC***	**NC***	**NC***	**NC***	**NC***	**NC***
Net Change in Total Emissions[b]	**(49.6)**	**(13.1)**	**(51.8)**	**(87.3)**	**(87.4)**	**(90.1)**	
Percent Change	**-0.8%**	**-0.2%**	**-0.8%**	**-1.2%**	**-1.3%**	**-1.4%**	

Note: Emissions values are presented in CO_2 equivalent mass units using IPCC AR4 GWP values.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent

NC (No Change)

* Indicates a new source for the current Inventory year

[a] Not included in emissions total.

[b] Excludes net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from International Bunker Fuels.

Table 9-3: Revisions to Annual Sinks (C Sequestration) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Component: Sinks from Land Use, Land-Use Change, and Forestry[a]	**1990**		**2005**		**2009**	**2010**	**2011**	**2012**	**Average Annual Change**
Forest Land Remaining Forest Land: Changes in Forest Carbon Stock	65.1		120.2		84.5	90.2	93.2	93.4	**76.7**
Cropland Remaining Cropland: Changes in Agricultural Soil Carbon Stock	(13.3)		1.1		1.8	1.8	1.8	1.5	**(4.3)**
Land Converted to Cropland	(2.4)		(1.0)		(0.6)	(0.6)	(0.6)	(0.7)	**(1.0)**
Grassland Remaining Grassland	7.6		(1.4)		4.9	4.9	4.9	4.8	**1.8**
Land Converted to Grassland	(0.1)		(0.7)		(0.3)	(0.3)	(0.3)	(0.2)	**(0.2)**
Settlements Remaining Settlements: Changes in Urban Tree Carbon Stock	NC		NC		NC	NC	NC	NC	**NC**
Other (Landfilled Yard Trimmings and Food Scraps)	(1.8)		0.6		0.4	0.4	0.3	0.3	**(0.7)**
Net Change in Sinks[a]	**55.3**		**118.8**		**90.7**	**96.4**	**99.3**	**98.9**	
Percent Change	**6.7%**		**11.5%**		**9.4%**	**10.0%**	**10.1%**	**10.1%**	

NC (No Change)

Note: Numbers in parentheses indicate an increase in C sequestration.

[a] The sinks value includes the positive C sequestration reported for *Forest Land Remaining Forest Land, Cropland Remaining Cropland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Other Land* plus the loss in C sequestration reported for *Land Converted to Cropland* and *Grassland Remaining Grassland*.

Note: Totals may not sum due to independent rounding.

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