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DRAFT INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS:

1990 – 2010

FEBRUARY 27, 2012

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All data tables of this document are available for the full time series 1990 through 2010, 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.

Table of Contents

List of Tables, Figures, and Boxes

Tables

Figures

Boxes

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 2010. 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 Revised 1996 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC/UNEP/OECD/IEA 1997), the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000), and the IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry (IPCC 2003). Additionally, the U.S. emission inventory has continued to incorporate new methodologies and data from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The structure of this report is consistent with the UNFCCC guidelines for inventory reporting.[4] For most source categories, the IPCC methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

[BEGIN BOX]

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 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

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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/UNEP/OECD/IEA 1997).

[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/2006/sbsta/eng/09.pdf>.

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

[6] See < http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5270.php>.

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 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 CO2 underground for sequestration or other reasons. Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. For calendar year 2010, the first year in which data were reported, facilities in 29 categories provided in 40 CFR part 98 were required to report their 2010 emissions by the September 30, 2011 reporting deadline[7]. 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 how to use facility-level GHGRP data to improve the national estimates presented in this inventory.

[END BOX]

ES.1. Background Information

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (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 their national greenhouse gas emission inventories.[8] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—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 emission inventories.

There are also several gases that do not have a direct global warming effect but indirectly affect terrestrial and/or solar radiation absorption by influencing the formation or destruction of greenhouse gases, including tropospheric and stratospheric ozone. These gases include carbon monoxide (CO), oxides of nitrogen (NO_x), and non-CH_4 volatile organic compounds (NMVOCs). Aerosols, which are extremely small particles or liquid droplets, such as those produced by sulfur dioxide (SO_2) or elemental carbon emissions, can also affect the absorptive characteristics of the atmosphere.

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 2005, concentrations of these greenhouse gases have increased globally by 36, 148, and 18 percent, respectively (IPCC 2007).

Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODS) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the entry into force of the Montreal Protocol. Since then, the production of ODS is being phased out. In recent years, use of ODS substitutes such as HFCs and PFCs has grown as they begin to be phased in as replacements for CFCs and

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

[8] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in the annexes of the Inventory report for informational purposes.

HCFCs. Accordingly, atmospheric concentrations of these substitutes have been growing (IPCC 2007).

Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect 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).[9] 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 2001). 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 teragrams (or million metric tons) of CO_2 equivalent (Tg CO_2 Eq.).[10,11] All gases in this Executive Summary are presented in units of Tg CO_2 Eq.

The UNFCCC reporting guidelines for national inventories were updated in 2006,[12] but continue to require the use of GWPs from the IPCC Second Assessment Report (SAR) (IPCC 1996). This requirement ensures that current estimates of aggregate greenhouse gas emissions for 1990 to 2010 are consistent with estimates developed prior to the publication of the IPCC Third Assessment Report (TAR) (IPCC 2001) and the IPCC Fourth Assessment Report (AR4) (IPCC 2007). Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. All estimates are provided throughout the report in both CO_2 equivalents and unweighted units. A comparison of emission values using the SAR GWPs versus the TAR and AR4 GWPs 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.

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

Gas	**GWP**
CO_2	1
CH_4*	21
N_2O	310
HFC-23	11,700
HFC-32	650
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

Source: IPCC (1996)

* The CH_4 GWP includes the direct effects and those indirect effects due

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[9] 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.

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

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

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

to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Global warming potentials are not provided for CO, NO_x, NMVOCs, SO_2, and aerosols because there is no agreed-upon method to estimate the contribution of gases that are short-lived in the atmosphere, spatially variable, or have only indirect effects on radiative forcing (IPCC 1996).

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

In 2010, total U.S. greenhouse gas emissions were 6,865.5 Tg or million metric tons CO_2 Eq. Total U.S. emissions have increased by 11.0 percent from 1990 to 2010, and emissions increased from 2009 to 2010 by 3.3 percent (222.5 Tg CO_2 Eq.). The increase from 2009 to 2010 was primarily due to an increase in economic output resulting in an increase in energy consumption across all sectors, and much warmer summer conditions resulting in an increase in electricity demand that was generated primarily by combusting coal and natural gas. Since 1990, U.S. emissions have increased at an average annual rate of 0.5 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 2010.

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

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

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

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg or million metric tons CO_2 Eq.)

Gas/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**5,100.5**	**6,114.2**	**6,026.2**	**6,127.5**	**5,928.6**	**5,503.4**	**5,718.8**
Fossil Fuel Combustion	4,742.1	5,757.4	5,666.6	5,771.2	5,579.5	5,214.7	5,406.8
Electricity Generation	1,820.8	2,402.1	2,346.4	2,412.8	2,360.9	2,146.4	2,258.4
Transportation	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5
Industrial	850.1	827.3	861.7	856.5	814.6	743.0	792.1
Residential	338.3	357.9	321.5	342.4	349.3	339.1	349.6
Commercial	219.0	223.5	208.6	219.4	225.1	224.4	228.6
U.S. Territories	27.9	50.0	50.3	46.1	39.8	41.7	41.6
Non-Energy Use of Fuels	115.8	139.6	138.0	130.4	135.0	118.2	119.4
Iron and Steel Production & Metallurgical Coke Production	99.6	66.0	68.9	71.1	66.1	42.1	54.3
Natural Gas Systems	37.6	30.1	30.1	31.0	32.8	32.2	32.3
Cement Production	33.3	45.2	45.8	44.5	40.5	29.0	30.5
Lime Production	11.5	14.4	15.1	14.6	14.3	11.2	13.2
Incineration of Waste	8.0	12.5	12.5	12.7	11.9	11.7	12.1
Limestone and Dolomite Use	5.1	6.8	8.0	7.7	6.3	7.6	10.0
Ammonia Production	13.0	9.2	8.8	9.1	7.9	7.9	8.7
Cropland Remaining Cropland	7.1	7.9	7.9	8.2	8.6	7.2	7.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.5	4.9	4.1	3.4	4.4
Soda Ash Production and Consumption	4.1	4.2	4.2	4.1	4.1	3.6	3.7
Petrochemical Production	3.3	4.2	3.8	3.9	3.4	2.7	3.3

Aluminum Production	6.8	4.1	3.8	4.3	4.5	3.0	3.0
Carbon Dioxide Consumption	1.4	1.3	1.7	1.9	1.8	1.8	2.2
Titanium Dioxide Production	1.2	1.8	1.8	1.9	1.8	1.6	1.9
Ferroalloy Production	2.2	1.4	1.5	1.6	1.6	1.5	1.5
Zinc Production	0.6	1.0	1.0	1.0	1.2	0.9	1.2
Phosphoric Acid Production	1.5	1.4	1.2	1.2	1.2	1.0	1.0
Wetlands Remaining Wetlands	1.0	1.1	0.9	1.0	1.0	1.1	1.0
Lead Production	0.5	0.6	0.6	0.6	0.6	0.5	0.5
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.1	0.2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(809.7)*	*(1,068.8)*	*(1,118.2)*	*(1,076.2)*	*(1,055.5)*	*(1,030.7)*	*(1,042.5)*
Wood Biomass and Ethanol Consumption[b]	*218.6*	*228.6*	*233.7*	*241.1*	*252.1*	*244.1*	*266.1*
International Bunker Fuels[b]	*111.8*	*109.7*	*128.4*	*127.6*	*133.7*	*123.1*	*124.7*
CH_4	**668.3**	**633.7**	**646.4**	**656.4**	**663.2**	**671.8**	**666.2**
Natural Gas Systems	189.6	198.5	199.5	205.5	208.0	220.5	215.0
Enteric Fermentation	133.8	139.0	141.4	143.8	143.4	142.6	141.3
Landfills	147.7	112.7	111.7	111.7	113.1	111.2	107.8
Coal Mining	84.1	56.8	58.1	57.8	66.9	70.1	72.6
Manure Management	31.7	47.9	48.4	52.7	51.8	50.7	52.0
Petroleum Systems	35.2	29.2	29.2	29.8	30.0	30.7	31.0
Wastewater Treatment	15.9	16.5	16.7	16.6	16.6	16.5	16.3
Rice Cultivation	7.1	6.8	5.9	6.2	7.2	7.3	8.6
Stationary Combustion	7.5	6.6	6.2	6.5	6.6	6.3	6.4
Abandoned Underground Coal Mines	6.0	5.5	5.5	5.3	5.3	5.1	5.0
Forest Land Remaining Forest Land	2.5	8.1	17.9	14.6	8.8	5.8	4.8
Mobile Combustion	4.7	2.5	2.3	2.2	2.0	2.0	2.0
Composting	0.3	1.6	1.6	1.7	1.7	1.6	1.6
Petrochemical Production	0.9	1.1	1.0	1.0	0.9	0.8	0.9
Iron and Steel Production & Metallurgical Coke Production	1.0	0.7	0.7	0.7	0.6	0.4	0.5
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.2*	*0.2*	*0.2*	*0.1*	*0.2*
N_2O	**327.7**	**346.2**	**352.0**	**352.2**	**334.5**	**322.6**	**325.7**
Agricultural Soil Management	211.7	227.7	226.6	227.2	229.7	224.6	223.8
Mobile Combustion	43.9	36.9	33.6	30.3	26.1	23.9	23.9
Stationary Combustion	12.3	20.6	20.8	21.2	21.2	20.8	22.6
Manure Management	14.8	17.6	18.4	18.5	18.3	18.2	18.3
Nitric Acid Production	17.4	16.2	15.9	18.9	16.1	14.3	16.7
Wastewater Treatment	3.5	4.7	4.8	4.8	4.9	5.0	5.0
N_2O from Product Uses	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Forest Land Remaining Forest Land	2.1	7.0	15.0	12.2	7.5	5.1	4.3
Adipic Acid Production	15.8	7.4	8.9	10.7	2.6	2.8	2.8
Composting	0.4	1.7	1.8	1.8	1.9	1.8	1.7
Settlements Remaining Settlements	1.0	1.5	1.5	1.6	1.5	1.4	1.5
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands	+	+	+	+	+	+	+
International Bunker Fuels[b]	*1.1*	*1.0*	*1.2*	*1.2*	*1.2*	*1.1*	*1.1*
HFCs	**36.9**	**120.2**	**123.5**	**129.5**	**129.4**	**125.7**	**135.4**
Substitution of Ozone Depleting	0.3	104.2	109.3	112.3	115.5	120.0	129.7

Substances							
HCFC-22 Production	36.4	15.8	13.8	17.0	13.6	5.4	5.4
Semiconductor Manufacture	0.2	0.2	0.3	0.3	0.3	0.3	0.3
PFCs	**20.6**	**6.2**	**6.0**	**7.5**	**6.6**	**5.6**	**5.6**
Semiconductor Manufacture	2.2	3.2	3.5	3.7	4.0	4.0	4.0
Aluminum Production	18.4	3.0	2.5	3.8	2.7	1.6	1.6
SF_6	**32.6**	**17.8**	**16.8**	**15.6**	**15.0**	**13.9**	**13.8**
Electrical Transmission and Distribution	26.7	13.9	13.0	12.2	12.2	11.8	11.8
Magnesium Production and Processing	5.4	2.9	2.9	2.6	1.9	1.1	1.1
Semiconductor Manufacture	0.5	1.0	1.0	0.8	0.9	1.0	1.0
Total	**6,186.6**	**7,238.3**	**7,170.9**	**7,288.8**	**7,077.4**	**6,643.0**	**6,865.5**
Net Emission (Sources and Sinks)	**5,376.9**	**6,169.5**	**6,052.7**	**6,212.6**	**6,021.9**	**5,612.3**	**5,823.0**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Parentheses indicate negative values or sequestration. The net CO_2 flux total includes both emissions and sequestration, and constitutes a net sink in the United States. Sinks are only included in net emissions total.

[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 2010. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing approximately 83.3 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 0.3 percent since 1990, resulted primarily from natural gas systems, enteric fermentation associated with domestic livestock, and decomposition of wastes in landfills. Agricultural soil 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 from semiconductor manufacturing and as a by-product of primary aluminum production, while electrical transmission and distribution systems accounted for most SF_6 emissions.

Figure ES-4: 2010 Greenhouse Gas Emissions by Gas (percentages based on Tg CO_2 Eq.)

Overall, from 1990 to 2010, total emissions of CO_2 increased by 618.3 Tg CO_2 Eq. (12.1 percent), and CH_4 emissions have decreased 2.1 Tg CO_2 Eq. (0.3 percent). N_2O emissions decreased by 2.0 Tg CO_2 Eq. (0.6 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 64.7 Tg CO_2 Eq. (71.7 percent). From 1990 to 2010, HFCs increased by 98.5 Tg CO_2 Eq. (266.8 percent), PFCs decreased by 15.1 Tg CO_2 Eq. (73.0 percent), and SF_6 decreased by 18.8 Tg CO_2 Eq. (57.6 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 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 15.2 percent of total emissions in 2010. The following sections describe each gas' 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. Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen about 36 percent (IPCC 2007), principally due to the combustion of fossil fuels. Within the United States, fossil fuel combustion accounted for 94.5 percent of CO_2 emissions in 2010. Globally, approximately 30,313 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2009, of which the United States accounted for about 18 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). In addition to fossil-fuel combustion, several other sources emit significant quantities of CO_2. These sources include, but are not limited to non-energy use of fuels, iron and steel production and cement production (Figure ES-5).

Figure ES-5: 2010 Sources of CO_2 Emissions

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 79 percent of GWP-weighted emissions since 1990, growing slowly from 77 percent of total GWP-weighted emissions in 1990 to 79 percent in 2010. Emissions of CO_2 from fossil fuel combustion increased at an average annual rate of 0.7 percent from 1990 to 2010. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 20 years, and (2) an overall growth in emissions from electricity generation and transportation activities. Between 1990 and 2010, CO_2 emissions from fossil fuel combustion increased from 4,742.1 Tg CO_2 Eq. to 5,406.8 Tg CO_2 Eq.—a 14.0 percent total increase over the twenty-one-year period. From 2009 to 2010, these emissions increased by 192.2 Tg CO_2 Eq. (3.7 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, 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: 2010 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure ES-7: 2010 End-Use Sector Emissions of CO_2, CH_4, and N_2O from Fossil Fuel Combustion

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.

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[13] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Statistics 2010* < http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm> EIA (2010a).

Table ES-3: CO_2 Emissions from Fossil Fuel Combustion by Fuel Consuming End-Use Sector (Tg or million metric tons CO_2 Eq.)

End-Use Sector	1990	2005	2006	2007	2008	2009	2010
Transportation	**1,489.0**	**1,901.3**	**1,882.6**	**1,899.1**	**1,794.5**	**1,724.6**	**1,741.0**
Combustion	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5
Electricity	3.0	4.7	4.5	5.1	4.7	4.5	4.5
Industrial	**1,536.9**	**1,564.2**	**1,573.7**	**1,571.9**	**1,511.8**	**1,345.0**	**1,429.7**
Combustion	850.1	827.3	861.7	856.5	814.6	743.0	792.1
Electricity	686.8	737.0	712.0	715.4	697.3	602.0	637.6
Residential	**931.4**	**1,214.7**	**1,152.4**	**1,205.9**	**1,192.2**	**1,125.6**	**1,193.0**
Combustion	338.3	357.9	321.5	342.4	349.3	339.1	349.6
Electricity	593.0	856.7	830.8	863.5	842.9	786.5	843.5
Commercial	**757.0**	**1,027.2**	**1,007.6**	**1,048.2**	**1,041.1**	**977.8**	**1,001.5**
Combustion	219.0	223.5	208.6	219.4	225.1	224.4	228.6
Electricity	538.0	803.7	799.0	828.8	816.0	753.5	772.9
U.S. Territories[a]	**27.9**	**50.0**	**50.3**	**46.1**	**39.8**	**41.7**	**41.6**
Total	**4,742.1**	**5,757.4**	**5,657.2**	**5,759.9**	**5,570.5**	**5,214.7**	**5,406.8**
Electricity Generation	**1,820.8**	**2,402.1**	**2,346.4**	**2,412.8**	**2,360.9**	**2,146.4**	**2,258.4**

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. Transportation activities (excluding international bunker fuels) accounted for 32 percent of CO_2 emissions from fossil fuel combustion in 2010.[14] Virtually all of the energy consumed in this end-use sector came from petroleum products. Nearly 65 percent of the emissions resulted from gasoline consumption for personal vehicle use. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft. From 1990 to 2010, transportation emissions rose by 17 percent due, in large part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 39 percent from 1990 to 2010, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period.

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 26 percent of CO_2 from fossil fuel combustion in 2010. Approximately 55 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 22 and 19 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2010. Both sectors relied heavily on electricity for meeting energy demands, with 71 and 77 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 these end-use sectors have increased 30 percent since 1990, 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 36 percent of U.S. energy from fossil fuels and emitted 42 percent of the CO_2 from

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[14] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 33.7 percent of U.S. emissions from fossil fuel combustion in 2010.

fossil fuel combustion in 2010. The type of fuel combusted by electricity generators has a significant effect on their emissions. For example, some electricity is generated with low CO_2 emitting energy technologies, particularly non-fossil options such as nuclear, hydroelectric, or geothermal energy. However, electricity generators rely on coal for over half of their total energy requirements and accounted for 95 percent of all coal consumed for energy in the United States in 2010. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Other significant CO_2 trends included the following:

- CO_2 emissions from non-energy use of fossil fuels have increased 3.5 Tg CO_2 Eq. (3.0 percent) from 1990 through 2010. Emissions from non-energy uses of fossil fuels were 119.4 Tg CO_2 Eq. in 2010, which constituted 2.1 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- CO_2 emissions from iron and steel production and metallurgical coke production increased by 12.2 Tg CO_2 Eq. (28.9 percent) from 2009 to 2010, upsetting a trend of decreasing emissions. Despite this, from 1990 through 2010 emissions are still down 45.5 percent (45.3 Tg CO_2 Eq.). This decline is due to the restructuring of the industry, technological improvements, and increased scrap utilization.
- In 2010, CO_2 emissions from cement production increased by 1.5 Tg CO_2 Eq. (5.1 percent) from 2009. After decreasing in 1991 by two percent from 1990 levels, cement production emissions grew every year through 2006; emissions decreased in the three years prior to 2010. Overall, from 1990 to 2010, emissions from cement production have decreased by 8.3 percent, a decrease of 2.8 Tg CO_2 Eq.
- Net CO_2 uptake from Land Use, Land-Use Change, and Forestry increased by 232.9 Tg CO_2 Eq. (28.8 percent) from 1990 through 2010. 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.

Methane Emissions

Methane (CH_4) is more than 20 times as effective as CO_2 at trapping heat in the atmosphere (IPCC 1996). Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 148 percent (IPCC 2007). 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: 2010 Sources of CH_4 Emissions

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

- Natural gas systems were the largest anthropogenic source category of CH_4 emissions in the United States in 2010 with 215.0 Tg CO_2 Eq. of CH_4 emitted into the atmosphere. Those emissions have increased by 25.4 Tg CO_2 Eq. (13.4 percent) since 1990.
- Enteric fermentation is the second largest anthropogenic source of CH_4 emissions in the United States. In 2010, enteric fermentation CH_4 emissions were 141.3 Tg CO_2 Eq. (21.2 percent of total CH_4 emissions), which represents an increase of 7.5 Tg CO_2 Eq. (5.6 percent) since 1990.
- Landfills are the third largest anthropogenic source of CH_4 emissions in the United States, accounting for 16.2 percent of total CH_4 emissions (107.8 Tg CO_2 Eq.) in 2010. From 1990 to 2010, CH_4 emissions from landfills decreased by 39.8 Tg CO_2 Eq. (27.0 percent), with small increases occurring in some interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted,[15] which has more than offset the additional CH_4 emissions resulting from an

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[15] 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.

increase in the amount of municipal solid waste landfilled.

- In 2010, CH_4 emissions from coal mining were 72.6 Tg CO_2 Eq., a 2.5 Tg CO_2 Eq. (3.5 percent) increase over 2009 emission levels. The overall decline of 11.5 Tg CO_2 Eq. (13.6 percent) from 1990 results from the mining of less gassy coal from underground mines and the increased use of CH_4 collected from degasification systems.
- Methane emissions from manure management increased by 64.0 percent since 1990, from 31.7 Tg CO_2 Eq. in 1990 to 52.0 Tg CO_2 Eq. in 2010. 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 1996). Since 1750, the global atmospheric concentration of N_2O has risen by approximately 18 percent (IPCC 2007). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, fuel combustion in motor vehicles, stationary fuel combustion, manure management and nitric acid production (see Figure ES-9).

Figure ES-9: 2010 Sources of N_2O Emissions

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

- In 2010, N_2O emissions from mobile combustion were 23.9 Tg CO_2 Eq. (approximately 7.3 percent of U.S. N_2O emissions). From 1990 to 2009, N_2O emissions from mobile combustion decreased by 45.6 percent. However, from 1990 to 1998 emissions increased by 25.6 percent, due to control technologies that reduced NO_x emissions while increasing N_2O emissions. Since 1998, newer control technologies have led to an overall decline in N_2O from this source.
- N_2O emissions from adipic acid production were 2.8 Tg CO_2 Eq. in 2010, and have decreased significantly since 1996 from the widespread installation of pollution control measures. Emissions from adipic acid production have decreased by 82.2 percent since 1990, and emissions from adipic acid production have remained consistently lower than pre-1996 levels since 1998.
- N_2O emissions from stationary combustion increased 10.4 Tg CO_2 Eq. (84.6 percent) from 1990 through 2010. 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.
- Agricultural soils accounted for approximately 68.7 percent of N_2O emissions in the United States in 2010. Estimated emissions from this source in 2010 were 223.8 Tg CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2010, although overall emissions were 5.8 percent higher in 2010 than in 1990.

HFC, PFC, and SF_6 Emissions

HFCs and PFCs are families of synthetic chemicals that are used as alternatives to ODS, 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, 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 1996).

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

Figure ES-10: 2010 Sources of HFCs, PFCs, and SF_6 Emissions

Some significant trends in U.S. HFC, PFC, and SF_6 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 129.7 Tg CO_2 Eq. in 2010. Emissions from ODS substitutes are both the largest and the fastest growing source of HFC, PFC, and SF_6 emissions. These emissions have been increasing as phase-out of ODS required under the Montreal Protocol came into effect, especially after 1994, when full market penetration was made for the first generation of new technologies featuring ODS substitutes.
- HFC emissions from the production of HCFC-22 decreased by 85.2 percent (31.0 Tg CO_2 Eq.) from 1990 through 2010, due to a steady decline in the emission rate of HFC-23 (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) and the use of thermal oxidation at some plants to reduce HFC-23 emissions.
- SF_6 emissions from electric power transmission and distribution systems decreased by 55.7 percent (14.9 Tg CO_2 Eq.) from 1990 to 2010, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.
- PFC emissions from aluminum production decreased by 91.5 percent (16.9 Tg CO_2 Eq.) from 1990 to 2010, due to both industry emission reduction efforts and declines in domestic aluminum production.

ES.3. Overview of Sector Emissions and Trends

In accordance with the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC/UNEP/OECD/IEA 1997), and the 2003 UNFCCC Guidelines on Reporting and Review (UNFCCC 2003), 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-one-year period of 1990 to 2010, total emissions in the Energy and Agriculture sectors grew by 662.1 Tg CO_2 Eq. (12.5 percent), and 45.0 Tg CO_2 Eq. (11.3 percent), respectively. Emissions also slightly increased in the Industrial Processes sector by 1.7 Tg CO_2 Eq. (0.6 percent) , while emissions from the Waste and Solvent and Other Product Use sectors decreased by 35.2 Tg CO_2 Eq. (21.0 percent) and less than 0.1 Tg CO_2 Eq. (0.4 percent), respectively. Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry sector (magnitude of emissions plus CO_2 flux from all LULUCF source categories) increased by 227.6 Tg CO_2 Eq. (28.6 percent).

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

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

Chapter/IPCC Sector	1990	2005	2006	2007	2008	2009	2010
Energy	5,287.6	6,297.0	6,203.2	6,304.8	6,126.0	5,756.7	5,949.7
Industrial Processes	313.7	335.1	342.7	356.5	330.8	281.6	315.4
Solvent and Other Product Use	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Agriculture	399.4	439.2	440.9	448.7	450.6	443.7	444.4
Land-Use Change and Forestry	13.8	25.6	43.2	37.6	27.4	20.5	19.0
Waste	167.7	137.2	136.5	136.7	138.2	136.0	132.5

Total Emissions	**6,186.6**		**7,238.3**	**7,170.9**	**7,288.8**	**7,077.4**	**6,643.0**	**6,865.5**
Land-Use Change and Forestry (Sinks)	(809.7)		(1068.8)	(1118.2)	(1076.2)	(1055.5)	(1030.7)	(1042.5)
Net Emissions (Emissions and Sinks)	**5,376.9**		**6,169.5**	**6,052.7**	**6,212.6**	**6,021.9**	**5,612.3**	**5,823.0**

* The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total.

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 2010. In 2010, approximately 85 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 15 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 (50 percent and 14 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 86.7 percent of total U.S. greenhouse gas emissions in 2010.

Figure ES-12: 2010 U.S. Energy Consumption by Energy Source

Industrial Processes

The Industrial Processes chapter contains by-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion. 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 and urea consumption, lime production, limestone and dolomite use (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, and zinc production. Additionally, emissions from industrial processes release HFCs, PFCs, and SF_6. Overall, emission sources in the Industrial Process chapter account for 4.6 percent of U.S. greenhouse gas emissions in 2010.

Solvent and Other Product Use

The Solvent and Other Product Use chapter contains greenhouse gas emissions that are produced as a by-product of various solvent and other product uses. In the United States, emissions from N_2O from product uses, the only source of greenhouse gas emissions from this sector, accounted for about 0.1 percent of total U.S. anthropogenic greenhouse gas emissions on a carbon equivalent basis in 2010.

Agriculture

The Agricultural 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 21.2 percent and 7.8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2010. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2010, accounting for 68.7 percent. In

2010, emission sources accounted for in the Agricultural chapters were responsible for 6.5 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 uptake (sequestration) of C in the United States. Forests (including vegetation, soils, and harvested wood) accounted for 88 percent of total 2010 net CO_2 flux, urban trees accounted for 9 percent, mineral and organic soil carbon stock changes accounted for 1 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total net flux in 2010. 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 5.5 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 2010 resulted in a net C sequestration of 1,042.5 Tg CO_2 Eq. (Table ES-5). This represents an offset of 18.2 percent of total U.S. CO_2 emissions, or 15.2 percent of total greenhouse gas emissions in 2010. Between 1990 and 2010, total land use, land-use change, and forestry net C flux resulted in a 28.8 percent increase in CO_2 sequestration, 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.

Table ES-5: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg or million metric tons CO_2 Eq.)

Sink Category	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Forest Land Remaining Forest Land	(701.4)	(940.9)	(963.5)	(959.2)	(938.3)	(910.6)	(921.8)
Cropland Remaining Cropland	(35.4)	(18.9)	(19.8)	(20.3)	(18.7)	(18.1)	(16.3)
Land Converted to Cropland	34.3	20.1	20.3	20.0	20.0	20.0	20.0
Grassland Remaining Grassland	(19.7)	(18.0)	(42.2)	(2.9)	(2.8)	(2.6)	(2.4)
Land Converted to Grassland	(6.3)	(11.7)	(12.2)	(10.9)	(10.8)	(10.7)	(10.7)
Settlements Remaining Settlements	(57.1)	(87.8)	(89.8)	(91.9)	(93.9)	(95.9)	(98.0)
Other (Landfilled Yard Trimmings and Food Scraps)	(24.2)	(11.6)	(11.0)	(10.9)	(10.9)	(12.7)	(13.3)
Total	**(809.7)**	**(1,068.8)**	**(1,118.2)**	**(1,076.2)**	**(1,055.5)**	**(1,030.7)**	**(1,042.5)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table ES-6. Liming of agricultural soils and urea fertilization in 2010 resulted in CO_2 emissions of 3.9 Tg CO_2 Eq. (3,906 Gg) and 3.5 Tg CO_2 Eq. (3,480 Gg), respectively. Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO_2 emissions of 1.0 Tg CO_2 Eq. (983 Gg), and nitrous oxide (N_2O) emissions of less than 0.05 Tg CO_2 Eq. The application of synthetic fertilizers to forest soils in 2010 resulted in direct N_2O emissions of 0.4 Tg CO_2 Eq. (1 Gg). Direct 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, direct N_2O emissions from fertilizer application to settlement soils in 2010 accounted for 1.5 Tg CO_2 Eq. (5 Gg). This represents an increase of 51 percent since 1990. Forest fires in 2010 resulted in methane (CH_4) emissions of 4.8 Tg CO_2 Eq. (231 Gg), and in N_2O emissions of 4.0 Tg CO_2 Eq. (21 Gg).

Table ES-6: Emissions from Land Use, Land-Use Change, and Forestry (Tg or million metric tons CO_2 Eq.)

Source Category	1990	2005	2006	2007	2008	2009	2010
CO_2	**8.1**	**8.9**	**8.8**	**9.2**	**9.6**	**8.2**	**8.4**
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.3	4.2	4.5	5.0	3.7	3.9
Cropland Remaining Cropland: Urea Fertilization	2.4	3.5	3.7	3.8	3.6	3.5	3.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.1	0.9	1.0	1.0	1.1	1.0
CH_4	**2.5**	**8.1**	**17.9**	**14.6**	**8.8**	**5.8**	**4.8**
Forest Land Remaining Forest Land: Forest Fires	2.5	8.1	17.9	14.6	8.8	5.8	4.8
N_2O	**3.1**	**8.5**	**16.5**	**13.8**	**9.0**	**6.5**	**5.8**
Forest Land Remaining Forest Land: Forest Fires	2.1	6.6	14.6	11.9	7.2	4.7	4.0
Forest Land Remaining Forest Land: Forest Soils	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Settlements Remaining Settlements: Settlement Soils	1.0	1.5	1.5	1.6	1.5	1.4	1.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total	**13.8**	**25.6**	**43.2**	**37.6**	**27.4**	**20.5**	**19.0**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

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 81.4 percent of this chapter's emissions, and 16.2 percent of total U.S. CH_4 emissions.[16] Additionally, wastewater treatment accounts for 16.1 percent of Waste emissions, 2.5 percent of U.S. CH_4 emissions, and 1.5 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 1.6 Tg CO_2 Eq. and 1.7 Tg CO_2 Eq., respectively. Overall, emission sources accounted for in the Waste chapter generated 1.9 percent of total U.S. greenhouse gas emissions in 2010.

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 six sectors (i.e., chapters) defined by the IPCC: Energy; Industrial Processes; Solvent 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-7 summarizes emissions from each of these sectors, and Figure ES-13 shows the trend in emissions by sector from 1990 to 2010.

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[16] 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 of the Inventory report.

Figure ES-13: Emissions Allocated to Economic Sectors

Table ES-7: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg or million metric tons CO_2 Eq.)

Implied Sectors	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Electric Power Industry	1,866.2	2,448.8	2,393.0	2,459.1	2,405.8	2,191.4	2,306.5
Transportation	1,545.2	2,017.4	1,994.4	2,003.8	1,890.6	1,812.9	1,828.4
Industry	1,564.5	1,452.5	1,488.5	1,497.2	1,448.0	1,327.5	1,400.1
Agriculture	443.6	510.6	532.2	533.8	522.5	510.1	509.2
Commercial	388.0	379.5	367.4	382.2	393.7	395.5	401.2
Residential	345.4	371.3	336.1	359.1	368.4	360.1	374.7
U.S. Territories	33.7	58.2	59.3	53.5	48.4	45.5	45.5
Total Emissions	**6,186.6**	**7,238.3**	**7,170.9**	**7,288.8**	**7,077.4**	**6,643.0**	**6,865.5**
Land Use, Land-Use Change, and Forestry (Sinks)	(809.7)	(1,068.8)	(1,118.2)	(1,076.2)	(1,055.5)	(1,030.7)	(1,042.5)
Net Emissions (Sources and Sinks)	**5,376.9**	**6,169.5**	**6,052.7**	**6,212.6**	**6,021.9**	**5,612.3**	**5,823.0**

Note: Totals may not sum due to independent rounding. Emissions include CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. See Table 2-12 for more detailed data.

Using this categorization, emissions from electricity generation accounted for the largest portion (34 percent) of U.S. greenhouse gas emissions in 2010. Transportation activities, in aggregate, accounted for the second largest portion (27 percent), while emissions from industry accounted for the third largest portion (20 percent) of U.S. greenhouse gas emissions in 2010. 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 19 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 7 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 accounted for 6 and 5 percent, respectively, 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-8 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.[17] 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 account for the largest share of U.S. greenhouse gas emissions (29 percent) in 2010. Transportation is the second largest contributor to total U.S. emissions (27 percent). The residential and commercial sectors contributed the next largest shares of total U.S. greenhouse gas emissions in 2010. 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.).

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[17] 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.

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 2010.

Table ES-8: U.S Greenhouse Gas Emissions by Economic Sector with Electricity-Related Emissions Distributed (Tg or million metric tons CO_2 Eq.)

Implied Sectors	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Industry	2,237.4	2,174.3	2,187.2	2,193.6	2,131.0	1,916.1	2,024.9
Transportation	1,548.3	2,022.2	1,999.0	2,008.9	1,895.4	1,817.5	1,833.0
Residential	939.4	1,198.9	1,182.3	1,227.0	1,225.2	1,164.7	1,190.5
Commercial	953.2	1,244.6	1,183.4	1,239.2	1,227.3	1,163.1	1,236.1
Agriculture	474.6	540.1	559.7	566.6	550.1	536.1	535.4
U.S. Territories	33.7	58.2	59.3	53.5	48.4	45.5	45.5
Total Emissions	**6,186.6**	**7,238.3**	**7,170.9**	**7,288.8**	**7,077.4**	**6,643.0**	**6,865.5**
Land Use, Land-Use Change, and Forestry (Sinks)	(809.7)	(1,068.8)	(1,118.2)	(1,076.2)	(1,055.5)	(1,030.7)	(1,042.5)
Net Emissions (Sources and Sinks)	**5,376.9**	**6,169.5**	**6,052.7**	**6,212.6**	**6,021.9**	**5,612.3**	**5,823.0**

See Table 2-14 for more detailed data.

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

[BEGIN BOX]

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 nonutilities combined—was the largest source of U.S. greenhouse gas emissions in 2010; (4) emissions per unit of total gross domestic product as a measure of national economic activity; and (5) emissions per capita.

Table ES-9 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 0.5 percent 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-9: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Growth Rate**[a]
GDP[b]	100	157	161	165	164	158	163	2.5%
Electricity Consumption[c]	100	134	135	137	136	131	137	1.6%
Fossil Fuel Consumption[c]	100	119	117	119	116	109	113	0.6%
Energy Consumption[c]	100	119	119	121	119	113	118	0.8%
Population[d]	100	118	120	121	122	123	123	1.1%
Greenhouse Gas Emissions[e]	100	117	116	118	114	107	111	0.5%

[a] Average annual growth rate

[b] Gross Domestic Product in chained 2005 dollars (BEA 2010)

[c] Energy content-weighted values (EIA 2010b)

[d] U.S. Census Bureau (2010)

[e] GWP-weighted values

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

Source: BEA (2010), U.S. Census Bureau (2010), and emission estimates in this report.

[END BOX]

Indirect Greenhouse Gases (CO, NO_x, NMVOCs, and SO_2)—To Be Updated

The reporting requirements of the UNFCCC[18] 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.

Since 1970, the United States has published estimates of annual emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2010, EPA 2009),[19] which are regulated under the Clean Air Act. Table ES-10 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 ES-10: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**
NO_x	**21,705**	**15,899**	**15,039**	**14,380**	**13,545**	**11,467**
Stationary Fossil Fuel Combustion	10,023	5,858	5,545	5,432	5,148	4,159
Mobile Fossil Fuel Combustion	10,862	9,012	8,488	7,965	7,441	6,206
Oil and Gas Activities	139	321	319	318	318	393
Waste Combustion	82	129	121	114	106	128
Industrial Processes	591	569	553	537	520	568
Solvent Use	1	3	4	4	4	3
Agricultural Burning	6	6	7	8	7	7
Waste	0	2	2	2	2	2
CO	**129,976**	**70,791**	**67,227**	**63,613**	**59,993**	**51,431**
Stationary Fossil Fuel Combustion	5,000	4,649	4,695	4,744	4,792	4,543
Mobile Fossil Fuel Combustion	119,360	62,692	58,972	55,253	51,533	43,355
Oil and Gas Activities	302	318	319	320	322	345
Waste Combustion	978	1,403	1,412	1,421	1,430	1,403
Industrial Processes	4,125	1,555	1,597	1,640	1,682	1,549
Solvent Use	5	2	2	2	2	2
Agricultural Burning	206	166	223	226	224	226
Waste	1	7	7	7	7	7
NMVOCs	**20,930**	**13,761**	**13,594**	**13,423**	**13,254**	**9,313**
Stationary Fossil Fuel Combustion	912	716	918	1,120	1,321	424
Mobile Fossil Fuel Combustion	10,932	6,330	6,037	5,742	5,447	4,151
Oil and Gas Activities	554	510	510	509	509	599
Waste Combustion	222	241	238	234	230	159
Industrial Processes	2,422	1,997	1,933	1,869	1,804	1,322
Solvent Use	5,216	3,851	3,846	3,839	3,834	2,583
Agricultural Burning	NA	NA	NA	NA	NA	NA
Waste	673	114	113	111	109	76
SO_2	**20,935**	**13,466**	**12,388**	**11,799**	**10,368**	**8,599**
Stationary Fossil Fuel Combustion	18,407	11,541	10,612	10,172	8,891	7,167

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[18] See <http://unfccc.int/resource/docs/cop8/08.pdf>.

[19] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2008).

Mobile Fossil Fuel Combustion	793		889	750	611	472	455
Oil and Gas Activities	390		181	182	184	187	154
Waste Combustion	38		24	24	24	23	24
Industrial Processes	1,307		831	818	807	795	798
Solvent Use	0		0	0	0	0	0
Agricultural Burning	NA		NA	NA	NA	NA	NA
Waste	0		1	1	1	1	1

Source: (EPA 2010, EPA 2009) except for estimates from field burning of agricultural residues.
NA (Not Available)
Note: Totals may not sum due to independent rounding.

Key Categories

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006) defines a key category as a "[source or sink category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both."[20] 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 2010 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 and Annex 1.

Figure ES-16: 2010 Key Categories

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 IPCC

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[20] See Chapter 7 "Methodological Choice and Recalculation" in IPCC (2000). <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

Good Practice Guidance (IPCC 2000) 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.

[BEGIN BOX]

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 2010) 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.

[END BOX]

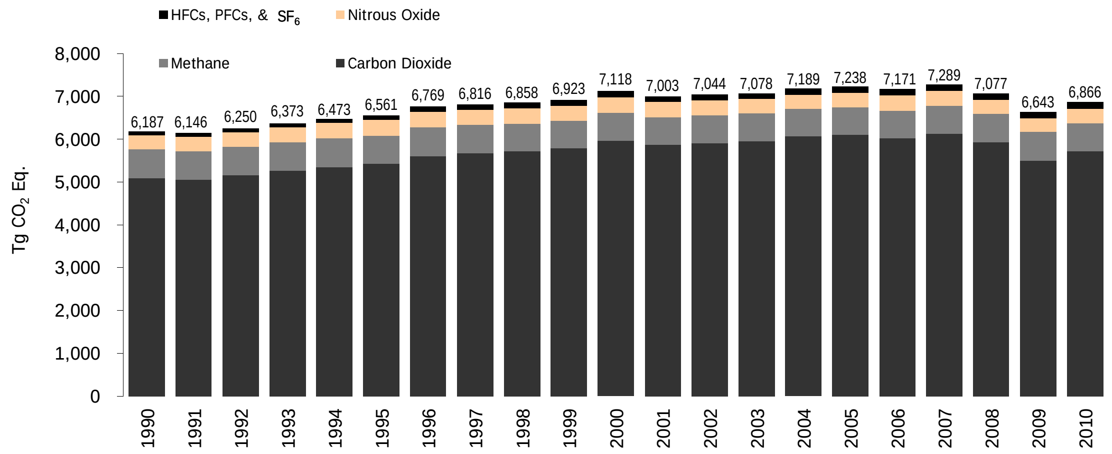


Figure ES-1: U.S. Greenhouse Gas Emissions by Gas

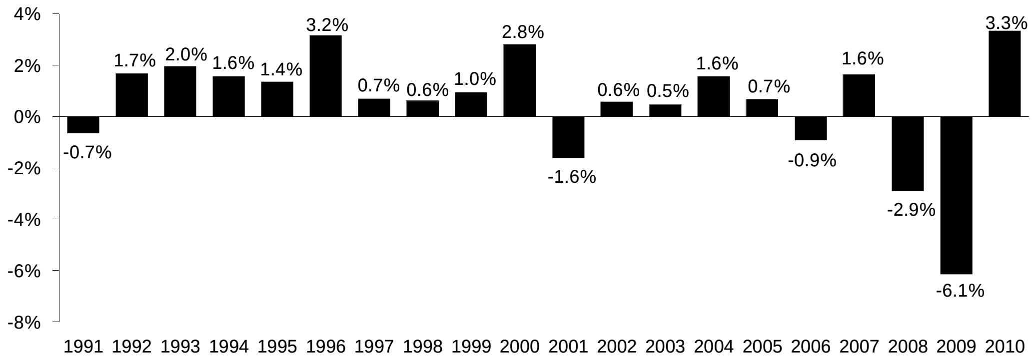


Figure ES-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

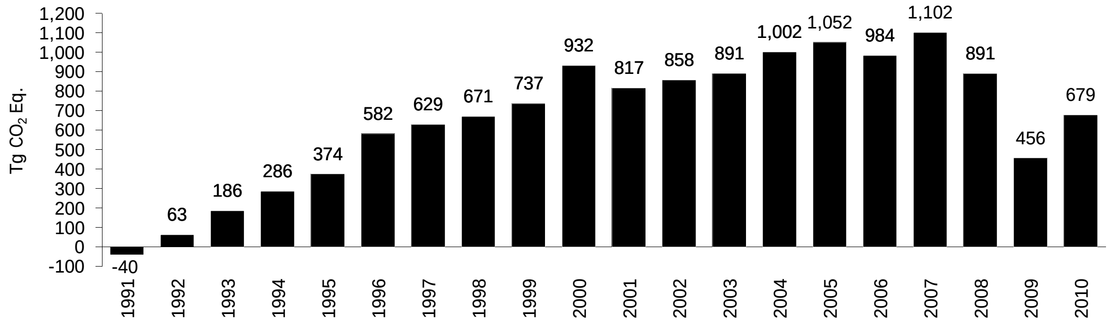


Figure ES-3: Cumulative Change in Annual U.S. Greenhouse Gas Emissions Relative to 1990

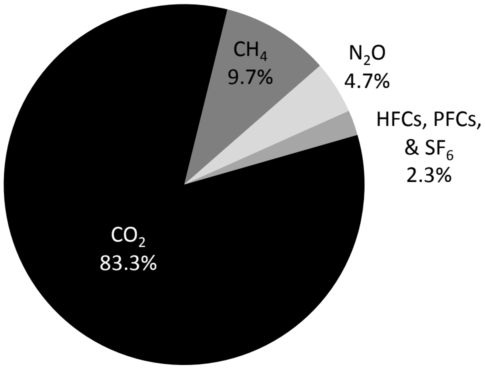


Figure ES-4: 2010 Greenhouse Gas Emissions by Gas (percents based on Tg CO_2 Eq.)

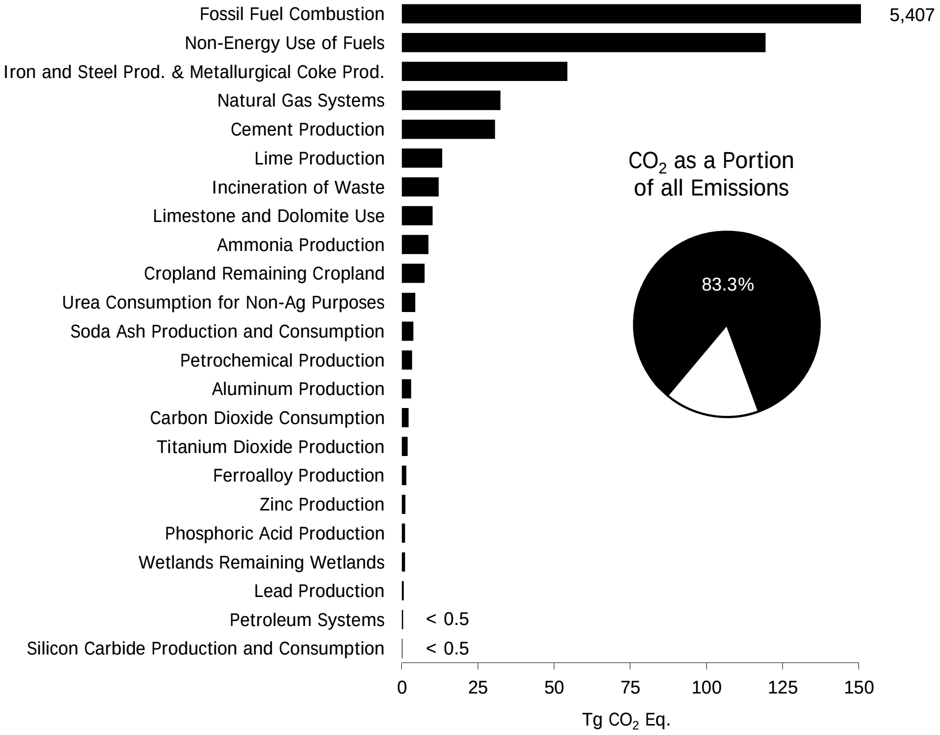


Figure ES-5: 2010 Sources of CO_2 Emissions

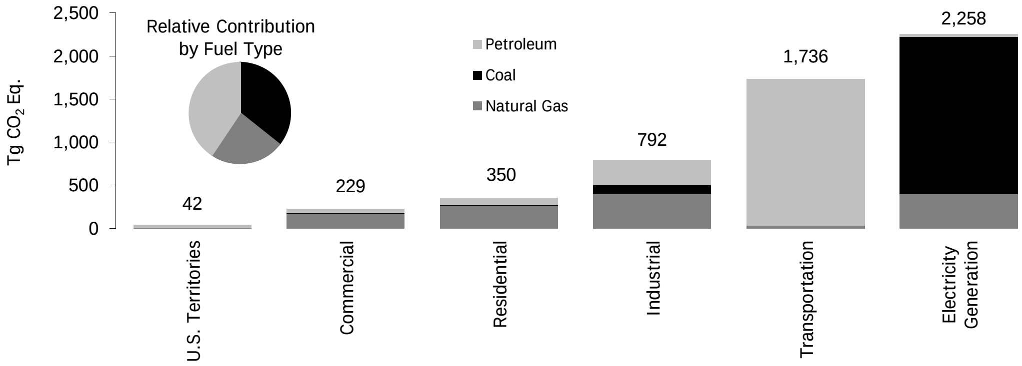


Figure ES-6: 2010 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: Electricity generation also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.

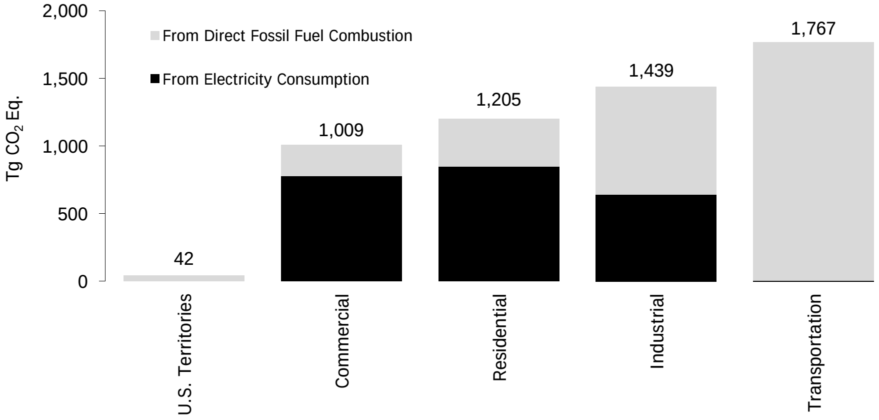


Figure ES-7: 2010 End-Use Sector Emissions of CO_2, CH_4, and N_2O from Fossil Fuel Combustion

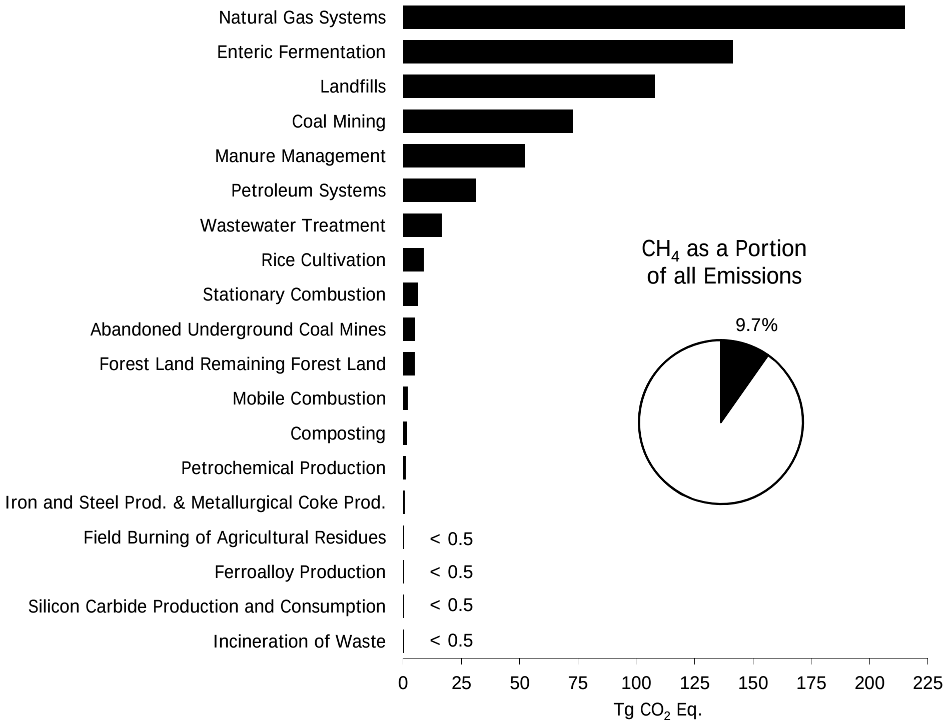


Figure ES-8: 2010 Sources of CH_4 Emissions

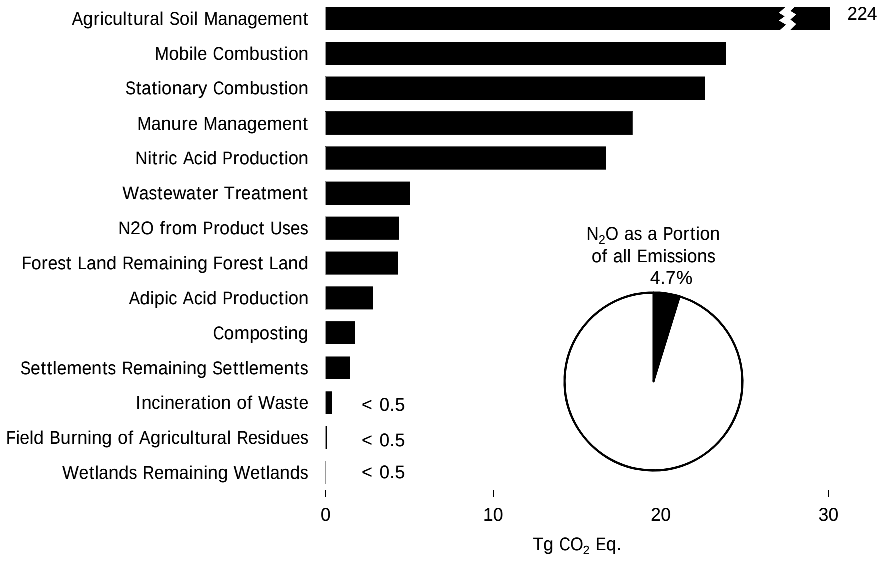


Figure ES-9: 2010 Sources of N_2O Emissions

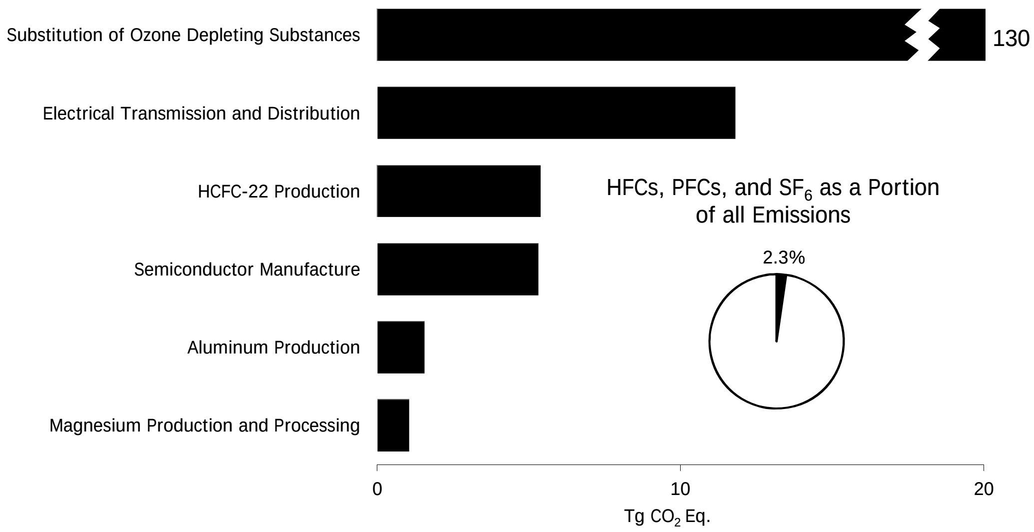
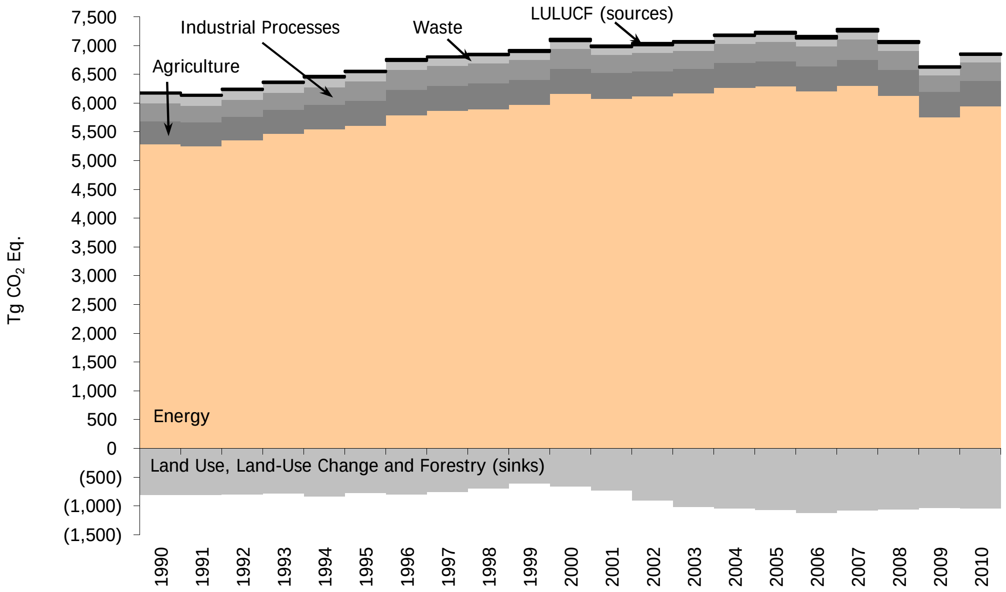


Figure ES-10: 2010 Sources of HFCs, PFCs, and SF_6 Emissions



Note: Relatively smaller amounts of GWP-weighted emissions are also emitted from the Solvent and Other Product Use sectors

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

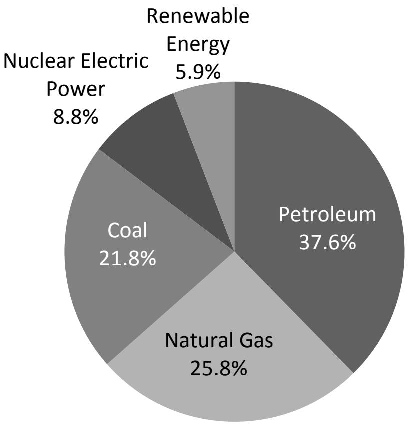


Figure ES-12: 2010 U.S. Energy Consumption by Energy Source

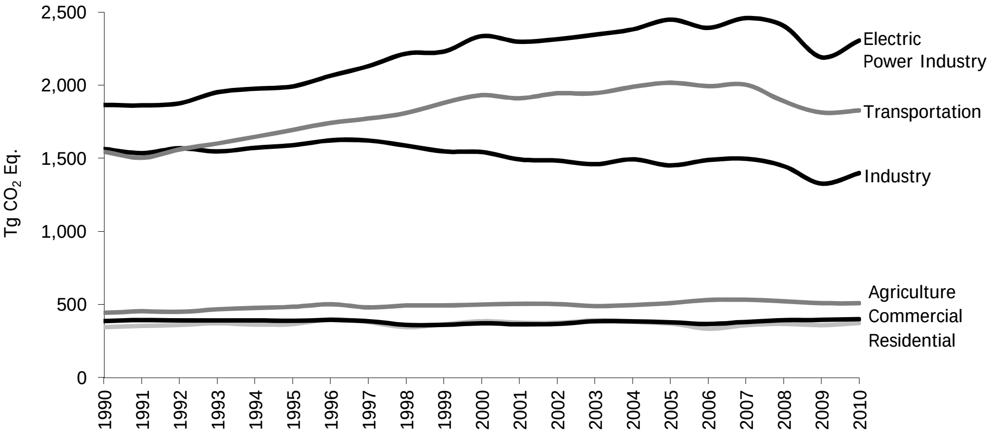


Figure ES-13: Emissions Allocated to Economic Sectors
Note: Does not include U.S. Territories.

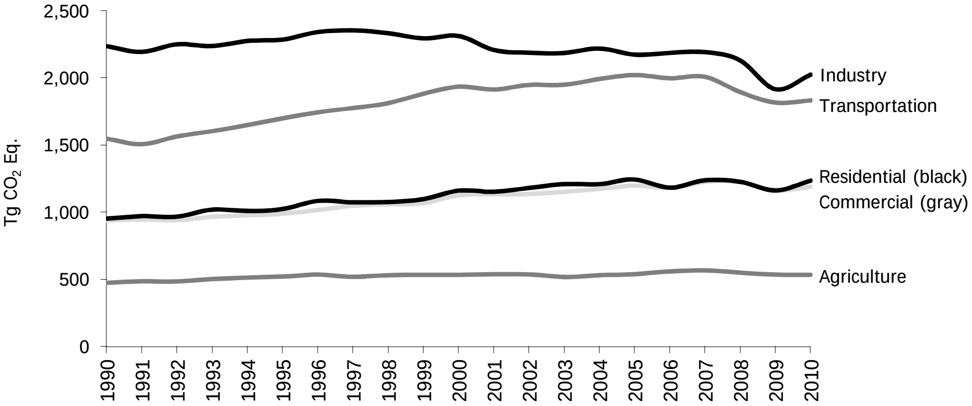


Figure ES-14: Emissions with Electricity Distributed to Economic Sectors

Note: Does not include U.S. Territories.

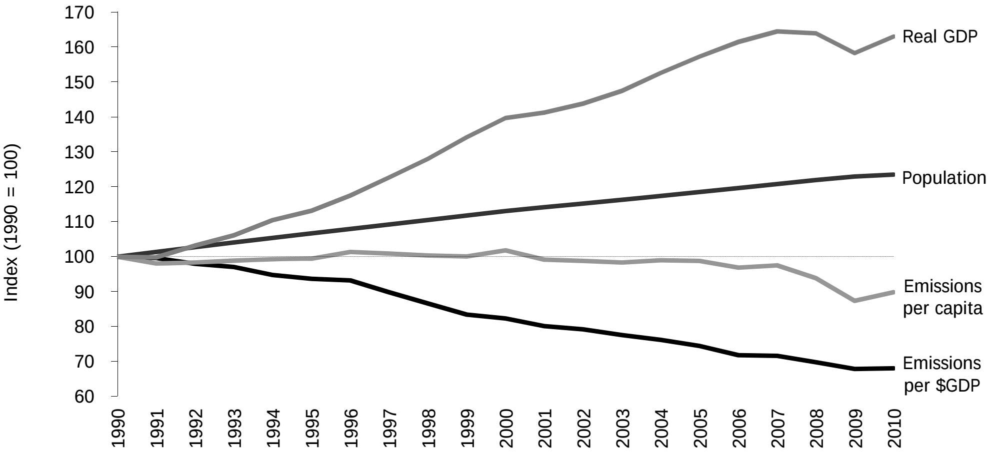


Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

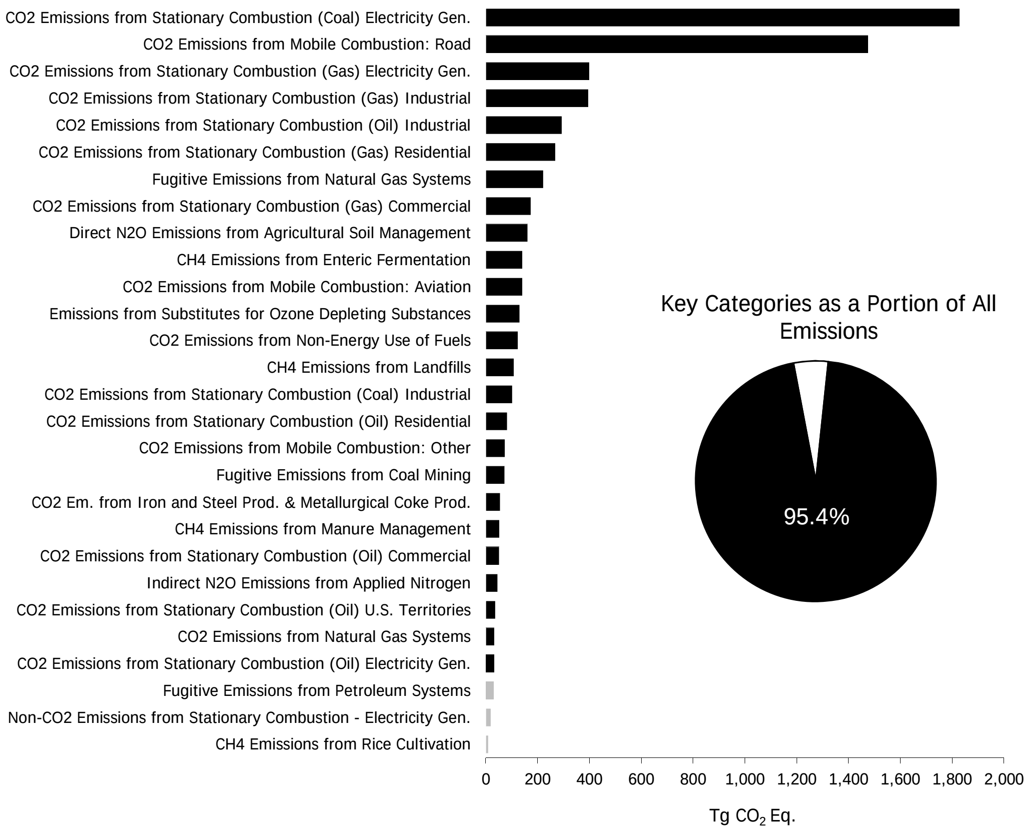


Figure ES-16: 2010 Key Categories

Notes: For a complete discussion of the key category analysis, see Annex 1.
Black bars indicate a Tier 1 level assessment key category.
Gray bars indicate a Tier 2 level assessment key category.

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 2010. 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 in order to show the relative contribution of each gas to global average radiative forcing.[21] 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."[22,23]

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…"[24] 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 accepted the Revised 1996 IPCC Guidelines at its Twelfth Session (Mexico City, September 11-13, 1996). This report presents information in accordance with these guidelines. In addition, this Inventory is in accordance with the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories and the Good Practice Guidance for Land Use, Land-Use Change, and Forestry, which further expanded upon the methodologies in the Revised 1996 IPCC Guidelines. The IPCC has also accepted the 2006 Guidelines for National Greenhouse Gas Inventories (IPCC 2006) at its Twenty-Fifth Session (Mauritius, April 2006). The 2006 IPCC Guidelines build on the previous bodies of work and includes 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." Many of the methodological improvements presented in the 2006 Guidelines have been adopted in this Inventory.

Overall, this inventory of anthropogenic greenhouse gas emissions 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.[25] The structure of this report is consistent with the current

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[21] See the section below entitled *Global Warming Potentials* for an explanation of GWP values.

[22] 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/UNEP/OECD/IEA 1997).

[23] 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)

[24] 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>.

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

UNFCCC Guidelines on Annual Inventories (UNFCCC 2006).

[BEGIN BOX]

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 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).[26] Additionally, the calculated emissions and sinks in a given year for the U.S. are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[27] 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 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 CO2 underground for sequestration or other reasons. Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. For calendar year 2010, the first year in which data were reported, facilities in 29 categories provided in 40 CFR part 98 were required to report their 2010 emissions by the September 30, 2011 reporting deadline[28]. 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 how to use facility-level GHGRP data to improve the national estimates presented in this inventory.

[END BOX]

1.1. Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal and oil, deforestation, and other sources have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere. These gases absorb some of the energy being radiated from the surface of the earth and trap it in the atmosphere, 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, because without them the planet's surface would be about 60 ºF cooler than present. But, as the concentrations of these gases continue to increase in the atmosphere, the Earth's temperature is climbing above past levels. According to NOAA and NASA data, the Earth's average surface temperature has increased by about 1.2 to 1.4 ºF since 1900. The ten warmest years on record (since 1850) have all occurred in the past 13 years (EPA 2009). 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.

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

[27] See <http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5270.php>

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

If greenhouse gases continue to increase, climate models predict that the average temperature at the Earth's surface could increase from 2.0 to 11.5 ºF above 1990 levels by the end of this century (IPCC 2007). 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. But they are not sure by how much it will change, at what rate it will change, or what the exact effects will be.[29]

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), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2001). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans.[30] A gauge of these changes is called radiative forcing, which is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system (IPCC 2001). 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).

> *Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).*

Naturally occurring greenhouse gases include water vapor, CO_2, methane (CH_4), nitrous oxide (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.[31] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—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 gases that, although they do not have a commonly agreed upon direct radiative forcing effect, do influence the global radiation budget. These tropospheric gases include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and 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 that are often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants. They can affect the absorptive characteristics of the atmosphere. Comparatively, however, the level of scientific understanding of aerosols is still very low (IPCC 2001).

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,

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

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

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

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	278 ppm	0.715 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration	385 ppm	1.741-1.865 ppm[a]	0.321-0.322 ppm[a]	5.6 ppt	74 ppt
Rate of concentration change	1.4 ppm/yr	0.005 ppm/yr[b]	0.26%/yr	Linear[c]	Linear[c]
Atmospheric lifetime (years)	50-200[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 (2009).

[a] The range is the annual arithmetic averages from a mid-latitude Northern-Hemisphere site and a mid-latitude Southern-Hemisphere site for October 2006 through September 2007 (CDIAC 2009).

[b] The growth rate for atmospheric CH_4 has been decreasing from 1.4 ppb/yr in 1984 to less than 0 ppb/yr in 2001, 2004, and 2005.

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

[d] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.

[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.

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). Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to affect directly the average global concentration of water vapor, but, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. While a warmer atmosphere has an increased water holding capacity, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (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 385 ppmv in 2008, a 37.5 percent increase (IPCC 2007 and NOAA/ESRL 2009).[32,33] The IPCC definitively states that "the present atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2" (IPCC 2001). 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 fourth assessment, the IPCC stated "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increased in anthropogenic greenhouse gas concentrations," of which CO_2 is the most important (IPCC 2007)

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

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

[33] 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).

mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 143 percent since 1750, from a pre-industrial value of about 722 ppb to 1,741-1,865 ppb in 2007[34], although the rate of increase has been declining. 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 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 may increase the atmospheric lifetime of CH_4 (IPCC 2001).

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 18 percent since 1750, from a pre-industrial value of about 270 ppb to 321-322 ppb in 2007[35], 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).

Ozone. Ozone is present in both the upper stratosphere,[36] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[37] 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 1996). The depletion of stratospheric ozone and its radiative forcing was expected to reach a maximum in about 2000 before starting to recover. As of IPCC's fourth assessment," whether or not recently observed changes in ozone trends are already indicative of recovery of the global ozone layer is not yet clear." (IPCC 2007)

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 2001)

Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride. 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

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[34] The range is the annual arithmetic averages from a mid-latitude Northern-Hemisphere site and a mid-latitude Southern-Hemisphere site for October 2006 through September 2007 (CDIAC 2009)

[35] The range is the annual arithmetic averages from a mid-latitude Northern-Hemisphere site and a mid-latitude Southern-Hemisphere site for October 2006 through September 2007 (CDIAC 2009).

[36] 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.

[37] 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.

importation of HCFCs by non-Article 5[38] 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, and SF_6 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 2001). PFCs and SF_6 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 and SF_6 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 2001).

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.

Nitrogen Oxides. 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 and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects.[39] Additionally, NO_x emissions from aircraft are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 1999). 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. They can be produced by natural events such as dust storms and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. Aerosols affect radiative forcing differently than greenhouse gases, and their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols is typically divided into two effects. The first effect involves decreased droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect involves an increase in the water content and lifetime of clouds due to the effect of reduced droplet size on precipitation efficiency (IPCC 2001). Recent research has placed a greater focus on the second indirect radiative forcing effect of aerosols.

Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic

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[38] 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.

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

aerosols, sulfates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous[40] aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning.

The net effect of aerosols on radiative forcing is believed to be negative (i.e., net cooling effect on the climate), although because they remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[41] Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). "However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result" (IPCC 1996).

The IPCC's Third Assessment Report notes that "the indirect radiative effect of aerosols is now understood to also encompass effects on ice and mixed-phase clouds, but the magnitude of any such indirect effect is not known, although it is likely to be positive" (IPCC 2001). Additionally, current research suggests that another constituent of aerosols, black carbon, has a positive radiative forcing, and that its presence "in the atmosphere above highly reflective surfaces such as snow and ice, or clouds, may cause a significant positive radiative forcing (IPCC 2007). The primary anthropogenic emission sources of black carbon include diesel exhaust and open biomass burning.

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 2001). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP weighted emissions are measured in teragrams of CO_2 equivalent (Tg CO_2 Eq.)[42] The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\mathrm{Tg\,CO_2\ Eq} = (\mathrm{Gg\ of\ gas}) \times (\mathrm{GWP}) \times \left(\frac{\mathrm{Tg}}{1{,}000\,\mathrm{Gg}}\right)$$

where,

Tg CO_2 Eq. = Teragrams of CO_2 Equivalents

Gg = Gigagrams (equivalent to a thousand metric tons)

GWP = Global Warming Potential

Tg = Teragrams

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. The parties to the UNFCCC have also agreed to use GWPs based upon a 100-year time horizon although other time horizon values are available.

> *Greenhouse gas emissions and removals should be presented on a gas-by-gas basis in units of mass... In addition, consistent with decision 2/CP.3, Parties should report aggregate emissions and removals of greenhouse gases, expressed in CO_2 equivalent terms at summary inventory level, using GWP values provided by the IPCC in its Second Assessment Report... based on the effects of greenhouse gases over a*

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[40] Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2001).

[41] 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).

[42] Carbon comprises 12/44$^{\text{ths}}$ of carbon dioxide by weight.

100-year time horizon.[43]

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) 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. No GWP values are attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

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

Gas	Atmospheric Lifetime	GWP[a]
CO_2	50-200	1
CH_4[b]	12±3	21
N_2O	120	310
HFC-23	264	11,700
HFC-32	5.6	650
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

Source: (IPCC 1996)

[a] 100-year time horizon

[b] 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.

[BEGIN BOX]

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

In 2007, the IPCC published its Fourth Assessment Report (AR4), which provided an updated and more comprehensive scientific assessment of climate change. Within this report, the GWPs of several gases were revised relative to the SAR and the IPCC's Third Assessment Report (TAR) (IPCC 2001). Thus the GWPs used in this report have been updated twice by the IPCC; although the SAR GWPs are used throughout this report, it is interesting to review the changes to the GWPs and the impact such improved understanding has on the total GWP-weighted emissions of the United States. Since the SAR and TAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function. The GWPs are drawn from IPCC/TEAP (2005) and the TAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. In addition, the values for radiative forcing and lifetimes have been recalculated for a variety of halocarbons, which were not presented in the SAR.

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[43] Framework Convention on Climate Change; <http://unfccc.int/resource/docs/cop8/08.pdf>; 1 November 2002; Report of the Conference of the Parties at its eighth session; held at New Delhi from 23 October to 1 November 2002; Addendum; Part One: Action taken by the Conference of the Parties at its eighth session; Decision -/CP.8; Communications from Parties included in Annex I to the Convention: Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention, Part 1: UNFCCC reporting guidelines on annual inventories; p. 7. (UNFCCC 2003)

Table 1-3 presents the new GWPs, relative to those presented in the SAR.

Table 1-3: Comparison of 100-Year GWPs

Gas	SAR	TAR	AR4	Change from SAR	
				TAR	AR4
CO_2	1	1	1	NC	0
CH_4*	21	23	25	2	4
N_2O	310	296	298	(14)	(12)
HFC-23	11,700	12,000	14,800	300	3,100
HFC-32	650	550	675	(100)	25
HFC-125	2,800	3,400	3,500	600	700
HFC-134a	1,300	1,300	1,430	NC	130
HFC-143a	3,800	4,300	4,470	500	670
HFC-152a	140	120	124	(20)	(16)
HFC-227ea	2,900	3,500	3,220	600	320
HFC-236fa	6,300	9,400	9,810	3,100	3,510
HFC-4310mee	1,300	1,500	1,640	200	340
CF_4	6,500	5,700	7,390	(800)	890
C_2F_6	9,200	11,900	12,200	2,700	3,000
$C_4F_1$0	7,000	8,600	8,860	1,600	1,860
C6F14	7,400	9,000	9,300	1,600	1,900
SF_6	23,900	22,200	22,800	(1,700)	(1,100)

Source: (IPCC 2007, IPCC 2001)
NC (No Change)
Note: Parentheses indicate negative values.
* 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.

To comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. The UNFCCC reporting guidelines for national inventories[44] were updated in 2002 but continue to require the use of GWPs from the SAR so that current estimates of aggregate greenhouse gas emissions for 1990 through 2010 are consistent and comparable with estimates developed prior to the publication of the TAR and AR4. For informational purposes, emission estimates that use the updated GWPs are presented in detail in Annex 6.1 of this report. All estimates provided throughout this report are also presented in unweighted units.

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1.2. Institutional 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, 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. The 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

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[44] See <http://unfccc.int/resource/docs/cop8/08.pdf>.

OAP serves as the 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 voluntary outreach efforts with EPA. Finally, the U.S. Department of State officially submits the Inventory to the UNFCCC each April.

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 IPCC Good Practice Guidance, IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry, 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 for printing, posted online, printed by the U.S. Government Printing Office, and made available for the public.

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 Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories

(IPCC/UNEP/OECD/IEA 1997). In addition, the United States references the additional guidance provided in the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000), the IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry (IPCC 2003), and 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 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 Revised 1996 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 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.

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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.

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1.5. Key Categories

The IPCC’s Good Practice Guidance (IPCC 2000) defines a key category as a “[source or sink category] that is prioritized within the national inventory system because its estimate has a significant influence on a country’s total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both.”[45] By definition, key categories include those sources that have the greatest contribution to the absolute level of national emissions. 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 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.

A Tier 1 approach, as defined in the IPCC’s Good Practice Guidance (IPCC 2000), 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 the Tier 1 approach, a Tier 2 approach, as defined in the IPCC’s Good Practice Guidance (IPCC 2000), was then implemented to identify any additional key categories not already identified in the Tier 1 assessment. This analysis, which includes each source categories’ uncertainty assessments (or proxies) in its

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[45] See Chapter 7 “Methodological Choice and Recalculation” in IPCC (2000). <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

calculations, was also performed twice to include or exclude LULUCF categories.

In addition to conducting Tier 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the IPCC's Good Practice Guidance (IPCC 2000), 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 with IPCC guidelines. If these emissions were included in the totals, bunker fuels would qualify as a key category according to the Tier 1 approach. 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 the Tier 2 approach. 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 2010. The table also indicates the criteria used in identifying these categories (i.e., level, trend, Tier 1, Tier 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 (1990-2010)

		Tier 1				**Tier 2**					
IPCC Source Categories	**Gas**	**Level Without LULUCF**	**Trend Without LULUCF**	**Level With LULUCF**	**Trend With LULUCF**	**Level Without LULUCF**	**Trend Without LULUCF**	**Level With LULUCF**	**Trend With LULUCF**	**Qual** [a]	**2010 Emissions (Tg CO_2 Eq.)**
Energy											
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		1,827.3
CO_2 Emissions from Mobile Combustion: Road	CO_2	•	•	•	•	•	•	•	•		1,475.6
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•	•	•	•		402.3
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		399.4
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•	•	•	•	•	•	•	•		293.8
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•		•		•		•			267.1
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•		•			172.4
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•	•	•	•		140.7
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•	•	•	•	•	•	•	•		119.4
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•		96.0
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•		•				81.8
CO_2 Emissions from Mobile Combustion: Other	CO_2	•	•	•	•						73.5
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•						50.8
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	•	•	•	•						36.7
CO_2 Emissions from Natural Gas Systems	CO_2	•	•	•	•	•	•	•	•		32.3

IPCC Source Categories	Gas	Tier 1				Tier 2				Qual[a]	2010 Emissions (Tg 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		
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	•	•	•	•	•	•	•	•		31.3
CO_2 Emissions from Mobile Combustion: Marine	CO_2	•	•	•	•		•				30.0
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2		•		•						5.5
Fugitive Emissions from Natural Gas Systems	CH_4	•		•		•	•	•			215.0
Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•		72.6
Fugitive Emissions from Petroleum Systems	CH_4	•	•	•	•	•	•	•	•		31.0
Non-CO_2 Emissions from Stationary Combustion – Residential	CH_4						•				3.5
N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•		•		•		20.3
Non-CO_2 Emissions from Stationary Combustion - Electricity Generation	N_2O		•		•	•	•	•	•		18.5
Non-CO_2 Emissions from Stationary Combustion – Industrial	N_2O					•	•				2.8
International Bunker Fuels[b]	Several									•	126.0
Industrial Processes											
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•		54.3
CO_2 Emissions from Cement Production	CO_2	•	•	•	•						30.5
CO_2 Emissions from Ammonia Production	CO_2		•								8.7
CO_2 Emissions from Aluminum Production	CO_2						•		•		3.0
N_2O Emissions from Nitric Acid Production	N_2O					•		•			16.7
N_2O Emissions from Adipic Acid Production	N_2O		•		•						2.8
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	•	•	•	•	•	•	•	•		129.7
SF_6 Emissions from Electrical Transmission and Distribution	HiGWP		•		•		•		•		11.8
HFC-23 Emissions from HCFC-22 Production	HiGWP	•	•	•	•		•		•		5.4
PFC Emissions from Aluminum Production	HiGWP		•		•		•	•	•		1.6
Agriculture											
CH_4 Emissions from Enteric Fermentation	CH_4	•	•	•	•	•		•			141.3
CH_4 Emissions from Manure Management	CH_4	•	•	•	•	•	•	•	•		52.0
CH_4 Emissions from Rice Cultivation	CH_4					•		•			8.6

IPCC Source Categories	Gas	Tier 1 Level Without LULUCF	Tier 1 Trend Without LULUCF	Tier 1 Level With LULUCF	Tier 1 Trend With LULUCF	Tier 2 Level Without LULUCF	Tier 2 Trend Without LULUCF	Tier 2 Level With LULUCF	Tier 2 Trend With LULUCF	Qual[a]	2010 Emissions (Tg CO_2 Eq.)
Direct N_2O Emissions from Agricultural Soil Management	N_2O	•	•	•	•	•	•	•	•		169.9
Indirect N_2O Emissions from Applied Nitrogen	N_2O	•		•		•	•	•	•		54.0
Waste											
CH_4 Emissions from Landfills	CH_4	•	•	•	•	•	•	•	•		107.8
CH_4 Emissions from Wastewater Treatment	CH_4					•					16.3
Land Use, Land Use Change, and Forestry											
CO_2 Removals from Changes in Forest Carbon Stocks	CO_2			•	•			•	•		(921.8)
CO_2 Removals from Urban Trees	CO_2			•	•			•	•		(98.0)
CO_2 Removals from Cropland Remaining Cropland	CO_2			•	•			•	•		(16.3)
CO_2 Removals from Landfilled Yard Trimmings and Food Scraps	CO_2				•			•	•		(13.3)
CO_2 Removals from Grassland Remaining Grassland	CO_2				•				•		(2.4)
CO_2 Removals from Land Converted to Cropland	CO_2			•	•			•	•		20.0
CH_4 Removals from Forest Fires	CH_4								•		4.8
N_2O Removals from Forest Fires	N_2O								•		4.0
Key Categories Subtotal Without LULUCF											**6,713.9**
Total Emissions Without LULUCF											**6,829.7**
Percent of Total Without LULUCF											**98.3%**
Key Categories Subtotal With LULUCF											**5,690.8**
Total Emissions With LULUCF											**5,806.2**
Percent of Total With LULUCF											**98.0%**

[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 1-1. These attributes include:

- specific detailed procedures and forms 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 the uncertainty of the inventory estimates;
- expert review as well as QC—for both the inventory estimates and the Inventory (which is the primary vehicle for disseminating the results of the inventory development process). In addition, the plan provides for public review of the Inventory;
- both Tier 1 (general) and Tier 2 (source-specific) quality controls and checks, as recommended by IPCC

Good Practice Guidance;

- consideration of secondary data quality and source-specific quality checks (Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates provides for more structured communication and integration with the suppliers of secondary information;
- record-keeping provisions to track which procedures have been followed, and the results of the QA/QC and uncertainty analysis, and contains feedback mechanisms for corrective action based on the results of the investigations, thereby providing for continual data quality improvement and guided research efforts;
- implementation 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;
- a schedule for multi-year implementation; and
- promotion of coordination and interaction 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 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 1-1: 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. Despite these uncertainties, the UNFCCC reporting guidelines follow the recommendation in the 1996 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1997) 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 the U.S. greenhouse gas emissions inventory was developed using the IPCC Tier 2 uncertainty estimation methodology. Estimates of quantitative uncertainty for the overall greenhouse gas emissions inventory are shown below, in Table 1-5.

The IPCC provides good practice guidance on two approaches—Tier 1 and Tier 2—to estimating uncertainty for individual source categories. Tier 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 IPCC Good Practice Guidance (IPCC 2000), 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 (Tg CO_2 Eq. and Percent)

Gas	**2009 Emission Estimate[a] (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[b] (Tg CO_2 Eq.)**		**(%)**		**Mean[c] (Tg CO_2 Eq.)**	**Standard Deviation[c] (Tg CO_2 Eq.)**
		Lower Bound[d]	**Upper Bound[d]**	**Lower Bound**	**Upper Bound**		
CO_2	5,504.8	5,436.6	5,813.8	-1%	6%	5,622.5	97.5
CH_4[e]	686.3	623.9	805.4	-9%	17%	702.8	45.3
N_2O[e]	295.6	261.7	425.3	-11%	44%	334.2	42.1
PFC, HFC & SF_6[e]	143.3	134.5	153.4	-6%	7%	143.7	4.8
Total	**6,630.0**	**6,584.2**	**7,033.6**	**-1%**	**6%**	**6,803.2**	**115.0**
Net Emissions (Sources and Sinks)	**5,614.9**	**5,512.3**	**6,055.1**	**-2%**	**8%**	**5,785.4**	**139.1**

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 3.1 Tg 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 2009.

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 reporter, 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 2010. Although this report is intended to be comprehensive, certain sources have been identified yet 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 Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC/UNEP/OECD/IEA 1997), and the 2006 UNFCCC Guidelines on Reporting and Review (UNFCCC 2006), this Inventory of U.S. Greenhouse Gas Emissions and Sinks is segregated into six 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.
Industrial Processes	By-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion.
Solvent and Other Product Use	Emissions, of primarily NMVOCs, resulting from the use of solvents and N_2O from product uses.
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.

Source: (IPCC/UNEP/OECD/IEA 1997)

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: 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.

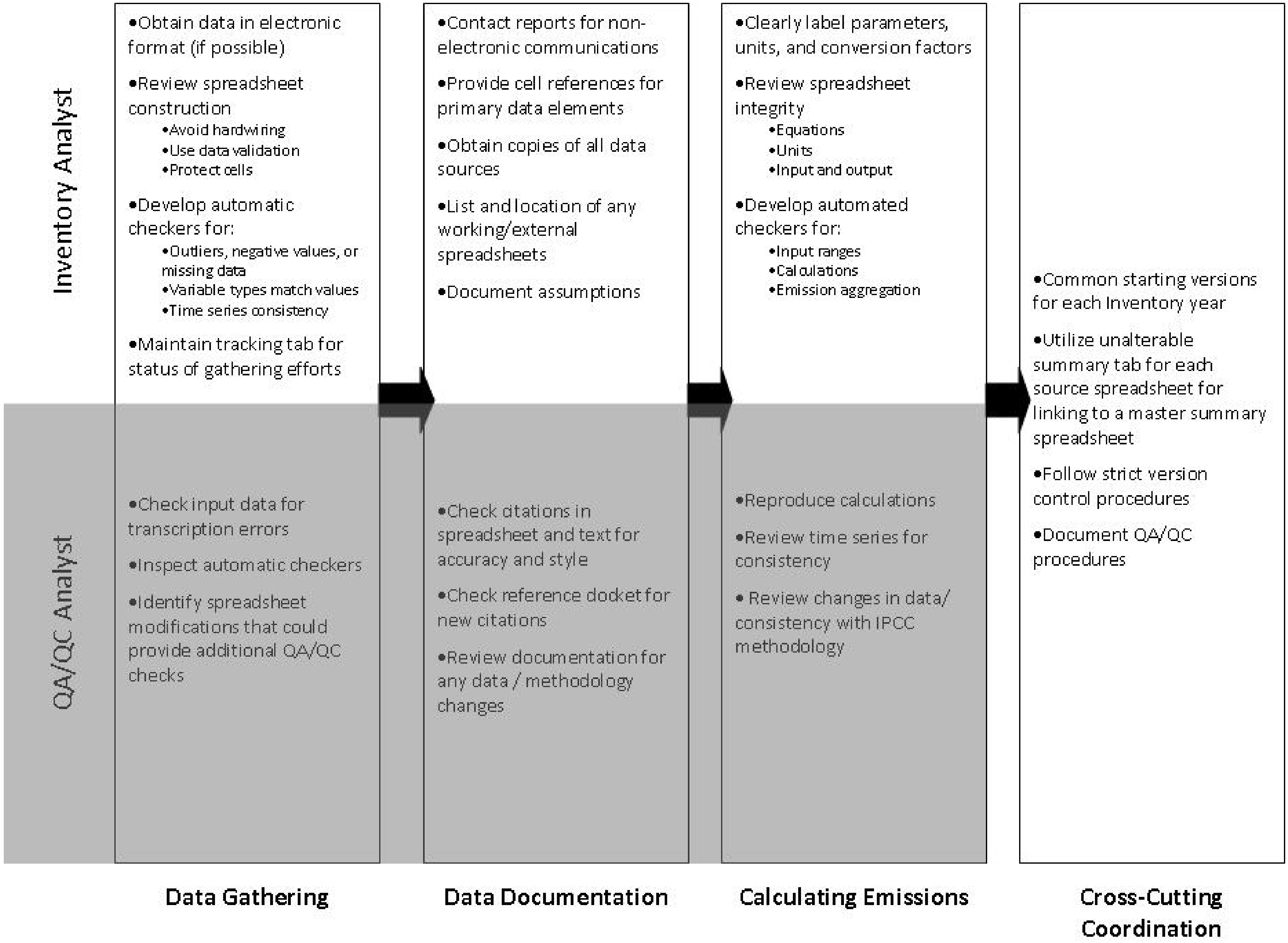
Planned Improvements: A discussion on any source-specific planned improvements, if applicable.

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 CH_4 Emissions from Coal Mining
  - 3.4. Methodology for Estimating CH_4 Emissions from Natural Gas Systems
  - 3.5. Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
  - 3.6. Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
  - 3.7. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
  - 3.8. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
  - 3.9. Methodology for Estimating CH_4 Emissions from Enteric Fermentation
  - 3.10. Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
  - 3.11. Methodology for Estimating N_2O Emissions and Soil Organic C Stock Changes from Agricultural Soil Management (Cropland and Grassland)
  - 3.12. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands
  - 3.13. 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
  - 7.4. Additional Information on Uncertainty Analyses by Source

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



	Data Gathering	Data Documentation	Calculating Emissions	Cross-Cutting Coordination

Inventory Analyst	•Obtain data in electronic format (if possible)
	•Review spreadsheet construction
	  •Avoid hardwiring
	  •Use data validation
	  •Protect cells
	•Develop automatic checkers for:
	  •Outliers, negative values, or missing data
	  •Variable types match values
	  •Time series consistency
	•Maintain tracking tab for status of gathering efforts
		•Contact reports for non-electronic communications
		•Provide cell references for primary data elements
		•Obtain copies of all data sources
		•List and location of any working/external spreadsheets
		•Document assumptions
			•Clearly label parameters, units, and conversion factors
			•Review spreadsheet integrity
			  •Equations
			  •Units
			  •Input and output
			•Develop automated checkers for:
			  •Input ranges
			  •Calculations
			  •Emission aggregation
				•Common starting versions for each Inventory year
				•Utilize unalterable summary tab for each source spreadsheet for linking to a master summary spreadsheet
				•Follow strict version control procedures
				•Document QA/QC procedures

QA/QC Analyst	•Check input data for transcription errors •Inspect automatic checkers •Identify spreadsheet modifications that could provide additional QA/QC checks	•Check citations in spreadsheet and text for accuracy and style •Check reference docket for new citations •Review documentation for any data / methodology changes	•Reproduce calculations •Review time series for consistency • Review changes in data/ consistency with IPCC methodology	

2. Trends in Greenhouse Gas Emissions

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

In 2010, total U.S. greenhouse gas emissions were 6,865.5 Tg or million metric tons CO_2 Eq. Total U.S. emissions have increased by 11.0 percent from 1990 to 2010, and emissions increased from 2009 to 2010 by 3.3 percent (222.5 Tg CO_2 Eq.). The increase from 2009 to 2010 was primarily due to an increase in economic output resulting in an increase in energy consumption across all sectors, and, much warmer summer conditions resulting in an increase in electricity demand that was generated primarily by combusting coal and natural gas. Since 1990, U.S. emissions have increased at an average annual rate of 0.5 percent.

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

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

As the largest contributor to U.S. greenhouse gas emissions, carbon dioxide (CO_2) from fossil fuel combustion has accounted for approximately 79 percent of global warming potential (GWP) weighted emissions since 1990, from 77 percent of total GWP-weighted emissions in 1990 to 79 percent in 2010. Emissions from this source category grew by 14.0 percent (664.8 Tg CO_2 Eq.) from 1990 to 2010 and were responsible for most of the increase in national emissions during this period. From 2009 to 2010, these emissions increased by 3.7 percent (192.2Tg 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 2006.

From 2006 to 2007, emissions from fuel combustion grew at a rate slightly higher than the average growth rate since 1990. There were a number of factors contributing to this increase. More energy-intensive weather conditions in both the winter and summer resulted in an increase in consumption of heating fuels, as well as an increase in the demand for electricity. This demand for electricity was met with an increase in coal consumption of 1.7 percent, and with an increase in natural gas consumption of 9.9 percent. This increase in fossil fuel consumption, combined with a 14.7 percent decrease in hydropower generation from 2006 to 2007, resulted in an increase in emissions in 2007. The increase in emissions from the residential and commercial sectors is a result of increased electricity consumption due to warmer summer conditions and cooler winter conditions compared to 2006. In addition to these more energy-intensive weather conditions, electricity prices remained relatively stable compared to 2006, and natural gas prices decreased slightly. Emissions from the industrial sector decreased compared to 2006 as a result of a decrease in industrial production and fossil fuels used for electricity generation. Despite an overall decrease in electricity generation from renewable energy in 2007 driven by decreases in hydropower generation, wind and solar generation increased significantly.

Emissions from fossil fuel combustion decreased from 2007 to 2008. Several factors contributed to this decrease in emissions. An increase in energy prices coupled with the economic downturn led to a decrease in energy demand and a resulting decrease in emissions from 2007 to 2008. In 2008, the price of coal, natural gas, and petroleum used to generate electricity, as well as the price of fuels used for transportation, increased significantly. As a result of this price increase, coal, natural gas, and petroleum consumption used for electricity generation decreased by 1.4 percent, 2.5 percent, and 28.8 percent, respectively. The increase in the cost of fuels to generate electricity translated into an increase in the price of electricity, leading to a decrease in electricity consumption across all sectors except the commercial sector. The increase in transportation fuel prices led to a decrease in vehicle miles traveled (VMT) and a 5.5 percent decrease in transportation fossil fuel combustion emissions from 2007 to 2008. Cooler weather conditions in the summer led to a decrease in cooling degree days by 8.7 percent and a decrease in electricity demand compared to 2007, whereas cooler winter conditions led to a 5.6 percent increase in heating degree days compared to 2007 and a resulting increase in demand for heating fuels. The increased emissions from winter heating energy demand was offset by a decrease in emissions from summer cooling related electricity demand. Lastly, renewable energy[46] consumption for electricity generation increased by 16.6 percent from 2007 to 2008, driven by a significant increase in solar and wind energy consumption (of 17.0 percent and 60.2 percent, respectively). This increase in renewable energy generation contributed to a decrease in the carbon intensity of electricity generation.

From 2008 to 2009, CO_2 from fossil fuel combustion emissions experienced a decrease of 6.5 percent, the greatest decrease of any year over the course of the twenty one-year period. Various factors contributed to this decrease in emissions. The continued economic downturn resulted in a 3.6 percent decrease in GDP, and a decrease in energy consumption across all sectors. The economic downturn also impacted total industrial production and manufacturing output, which decreased by 11.2 and 13.5 percent, respectively. In 2009, the price of coal used to generate electricity increased, while the price of natural gas used to generate electricity decreased significantly. As a result, natural gas was used for a greater share of electricity generation in 2009 than 2008, and coal was used for a smaller share. The fuel switching from coal to natural gas and additional electricity generation from other energy sources in 2009, which included a 6.3 percent increase in hydropower generation from the previous year, resulted in a decrease in carbon intensity, and in turn, a decrease in emissions from electricity generation. From 2008 to 2009, industrial sector emissions decreased significantly as a result of a decrease in output from energy-intensive industries of 23.6 percent in nonmetallic mineral and 30.3 percent in primary metal industries. The residential and commercial sectors only experienced minor decreases in emissions as summer and winter weather conditions were less energy-intensive from 2008 to 2009, and the price of electricity only increased slightly. Heating degree days decreased slightly and cooling degree days decreased by 3.8 percent from 2008 to 2009.

From 2009 to 2010, CO_2 emissions from fossil fuel combustion increased by 3.7 percent, which represents the largest annual increase in CO_2 emissions from fossil fuel combustion for the twenty one-year period.[47] This increase is primarily due to an increase in economic output 2009 to 2010, where total industrial production and manufacturing output increased by 5.3 and 5.8 percent, respectively (FRB 2011). Carbon dioxide emissions from fossil fuel combustion in the industrial sector increased by 6.6 percent, which was driven by a 15.2 percent increase in emissions from coal. Overall, coal consumption increased by 5.4 percent, the largest increase in coal consumption for the twenty one-year period. In 2010, weather conditions remained fairly constant in the winter and much hotter in the summer compared to 2009, as heating degree days decreased slightly (0.7 percent) and cooling degree days increased by 19 percent to their highest levels in the twenty one-year period. 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 6.3 percent and 1.7 percent, respectively.

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

[47] This increase also represents the largest absolute and percentage increase since 1988 (EIA 2011a).

Overall, from 1990 to 2010, total emissions of CO_2increased by 618.3 Tg CO_2 Eq. (12.1 percent), while total emissions of CH_4 and N_2O decreased by 2.1 Tg CO_2 Eq. (0.3 percent), and 2.0 Tg CO_2 Eq. (0.6 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 64.7 Tg CO_2 Eq. (71.7 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have extremely high GWPs and, in the cases of PFCs and SF_6, 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 15.2 percent of total emissions in 2010.

Table 2-1 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of Tg CO_2 Eq., while unweighted gas emissions and sinks in gigagrams (Gg) are provided in Table 2-2.

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

Gas/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**5,100.5**	**6,114.2**	**6,026.2**	**6,127.5**	**5,928.6**	**5,503.4**	**5,718.8**
Fossil Fuel Combustion	4,742.1	5,757.4	5,666.6	5,771.2	5,579.5	5,214.7	5,406.8
Electricity Generation	1,820.8	2,402.1	2,346.4	2,412.8	2,360.9	2,146.4	2,258.4
Transportation	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5
Industrial	850.1	827.3	861.7	856.5	814.6	743.0	792.1
Residential	338.3	357.9	321.5	342.4	349.3	339.1	349.6
Commercial	219.0	223.5	208.6	219.4	225.1	224.4	228.6
U.S. Territories	27.9	50.0	50.3	46.1	39.8	41.7	41.6
Non-Energy Use of Fuels	115.8	139.6	138.0	130.4	135.0	118.2	119.4
Iron and Steel Production & Metallurgical Coke Production	99.6	66.0	68.9	71.1	66.1	42.1	54.3
Natural Gas Systems	37.6	30.1	30.1	31.0	32.8	32.2	32.3
Cement Production	33.3	45.2	45.8	44.5	40.5	29.0	30.5
Lime Production	11.5	14.4	15.1	14.6	14.3	11.2	13.2
Incineration of Waste	8.0	12.5	12.5	12.7	11.9	11.7	12.1
Limestone and Dolomite Use	5.1	6.8	8.0	7.7	6.3	7.6	10.0
Ammonia Production	13.0	9.2	8.8	9.1	7.9	7.9	8.7
Cropland Remaining Cropland	7.1	7.9	7.9	8.2	8.6	7.2	7.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	3.5	4.9	4.1	3.4	4.4
Soda Ash Production and Consumption	4.1	4.2	4.2	4.1	4.1	3.6	3.7
Petrochemical Production	3.3	4.2	3.8	3.9	3.4	2.7	3.3
Aluminum Production	6.8	4.1	3.8	4.3	4.5	3.0	3.0
Carbon Dioxide Consumption	1.4	1.3	1.7	1.9	1.8	1.8	2.2
Titanium Dioxide Production	1.2	1.8	1.8	1.9	1.8	1.6	1.9
Ferroalloy Production	2.2	1.4	1.5	1.6	1.6	1.5	1.5
Zinc Production	0.6	1.0	1.0	1.0	1.2	0.9	1.2
Phosphoric Acid Production	1.5	1.4	1.2	1.2	1.2	1.0	1.0
Wetlands Remaining Wetlands	1.0	1.1	0.9	1.0	1.0	1.1	1.0
Lead Production	0.5	0.6	0.6	0.6	0.6	0.5	0.5
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.1	0.2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(809.7)*	*(1,068.8)*	*(1,118.2)*	*(1,076.2)*	*(1,055.5)*	*(1,030.7)*	*(1,042.5)*
Wood Biomass and Ethanol	*218.6*	*228.6*	*233.7*	*241.1*	*252.1*	*244.1*	*266.1*

Consumption[b]							
International Bunker Fuels[b]	*111.8*	*109.7*	*128.4*	*127.6*	*133.7*	*123.1*	*124.7*
CH_4	**668.3**	**633.7**	**646.4**	**656.4**	**663.2**	**671.8**	**666.2**
Natural Gas Systems	189.6	198.5	199.5	205.5	208.0	220.5	215.0
Enteric Fermentation	133.8	139.0	141.4	143.8	143.4	142.6	141.3
Landfills	147.7	112.7	111.7	111.7	113.1	111.2	107.8
Coal Mining	84.1	56.8	58.1	57.8	66.9	70.1	72.6
Manure Management	31.7	47.9	48.4	52.7	51.8	50.7	52.0
Petroleum Systems	35.2	29.2	29.2	29.8	30.0	30.7	31.0
Wastewater Treatment	15.9	16.5	16.7	16.6	16.6	16.5	16.3
Rice Cultivation	7.1	6.8	5.9	6.2	7.2	7.3	8.6
Stationary Combustion	7.5	6.6	6.2	6.5	6.6	6.3	6.4
Abandoned Underground Coal Mines	6.0	5.5	5.5	5.3	5.3	5.1	5.0
Forest Land Remaining Forest Land	2.5	8.1	17.9	14.6	8.8	5.8	4.8
Mobile Combustion	4.7	2.5	2.3	2.2	2.0	2.0	2.0
Composting	0.3	1.6	1.6	1.7	1.7	1.6	1.6
Petrochemical Production	0.9	1.1	1.0	1.0	0.9	0.8	0.9
Iron and Steel Production & Metallurgical Coke Production	1.0	0.7	0.7	0.7	0.6	0.4	0.5
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.2*	*0.2*	*0.2*	*0.1*	*0.2*
N_2O	**327.7**	**346.2**	**352.0**	**352.2**	**334.5**	**322.6**	**325.7**
Agricultural Soil Management	211.7	227.7	226.6	227.2	229.7	224.6	223.8
Mobile Combustion	43.9	36.9	33.6	30.3	26.1	23.9	23.9
Stationary Combustion	12.3	20.6	20.8	21.2	21.2	20.8	22.6
Manure Management	14.8	17.6	18.4	18.5	18.3	18.2	18.3
Nitric Acid Production	17.4	16.2	15.9	18.9	16.1	14.3	16.7
Wastewater Treatment	3.5	4.7	4.8	4.8	4.9	5.0	5.0
N_2O from Product Uses	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Forest Land Remaining Forest Land	2.1	7.0	15.0	12.2	7.5	5.1	4.3
Adipic Acid Production	15.8	7.4	8.9	10.7	2.6	2.8	2.8
Composting	0.4	1.7	1.8	1.8	1.9	1.8	1.7
Settlements Remaining Settlements	1.0	1.5	1.5	1.6	1.5	1.4	1.5
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands	+	+	+	+	+	+	+
International Bunker Fuels[b]	*1.1*	*1.0*	*1.2*	*1.2*	*1.2*	*1.1*	*1.1*
HFCs	**36.9**	**120.2**	**123.5**	**129.5**	**129.4**	**125.7**	**135.4**
Substitution of Ozone Depleting Substances	0.3	104.2	109.3	112.3	115.5	120.0	129.7

HCFC-22 Production	36.4	15.8	13.8	17.0	13.6	5.4	5.4
Semiconductor Manufacture	0.2	0.2	0.3	0.3	0.3	0.3	0.3
PFCs	**20.6**	**6.2**	**6.0**	**7.5**	**6.6**	**5.6**	**5.6**
Semiconductor Manufacture	2.2	3.2	3.5	3.7	4.0	4.0	4.0
Aluminum Production	18.4	3.0	2.5	3.8	2.7	1.6	1.6
SF_6	**32.6**	**17.8**	**16.8**	**15.6**	**15.0**	**13.9**	**13.8**
Electrical Transmission and Distribution	26.7	13.9	13.0	12.2	12.2	11.8	11.8
Magnesium Production and Processing	5.4	2.9	2.9	2.6	1.9	1.1	1.1
Semiconductor Manufacture	0.5	1.0	1.0	0.8	0.9	1.0	1.0
Total	**6,186.6**	**7,238.3**	**7,170.9**	**7,288.8**	**7,077.4**	**6,643.0**	**6,865.5**
Net Emissions (Sources and Sinks)	**5,376.9**	**6,169.5**	**6,052.7**	**6,212.6**	**6,021.9**	**5,612.3**	**5,823.0**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total. Parentheses indicate negative values or sequestration.

[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 (Gg)

Gas/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**5,100,461**	**6,114,211**	**6,026,196**	**6,127,525**	**5,928,635**	**5,503,446**	**5,718,794**
Fossil Fuel Combustion	4,742,080	5,757,404	5,666,588	5,771,185	5,579,548	5,214,694	5,406,848
Electricity Generation	1,820,818	2,402,142	2,346,406	2,412,827	2,360,920	2,146,417	2,258,360
Transportation	1,485,937	1,896,606	1,878,125	1,893,994	1,789,840	1,720,145	1,736,485
Industrial	850,132	827,273	861,678	856,487	814,551	743,020	792,137
Residential	338,347	357,903	321,513	342,397	349,318	339,071	349,584
Commercial	218,964	223,512	208,582	219,356	225,074	224,391	228,633
U.S. Territories	27,882	49,968	50,284	46,123	39,845	41,650	41,649
Non-Energy Use of Fuels	115,847	139,559	138,005	130,414	135,012	118,206	119,356
Iron and Steel Production & Metallurgical Coke Production	99,593	66,000	68,854	71,138	66,092	42,113	54,276
Natural Gas Systems	37,574	30,140	30,118	31,047	32,811	32,165	32,297
Cement Production	33,278	45,197	45,792	44,538	40,531	29,018	30,509
Lime Production	11,533	14,379	15,100	14,595	14,330	11,225	13,151
Incineration of Waste	7,989	12,468	12,531	12,727	11,888	11,703	12,054
Limestone and Dolomite Use	5,127	6,768	8,035	7,702	6,276	7,649	10,017
Ammonia Production	13,047	9,196	8,781	9,074	7,883	7,855	8,678
Cropland Remaining Cropland	7,084	7,854	7,875	8,222	8,626	7,159	7,387
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	3,519	4,944	4,065	3,415	4,365
Soda Ash Production and Consumption	4,141	4,228	4,162	4,140	4,099	3,554	3,735

Petrochemical Production	3,311	4,181	3,837	3,931	3,449	2,735	3,336
Aluminum Production	6,831	4,142	3,801	4,251	4,477	3,009	3,009
Carbon Dioxide Consumption	1,416	1,321	1,709	1,867	1,780	1,784	2,203
Titanium Dioxide Production	1,195	1,755	1,836	1,930	1,809	1,648	1,876
Ferroalloy Production	2,152	1,392	1,505	1,552	1,599	1,469	1,469
Zinc Production	632	1,030	1,030	1,025	1,159	943	1,168
Phosphoric Acid Production	1,529	1,386	1,167	1,166	1,187	1,018	1,017
Wetlands Remaining Wetlands	1,033	1,079	879	1,012	992	1,089	983
Lead Production	516	553	560	562	551	525	542
Petroleum Systems	394	305	306	310	297	325	337
Silicon Carbide Production and Consumption	375	219	207	196	175	145	181
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(809,680)*	*(1,068,841)*	*(1,118,183)*	*(1,076,167)*	*(1,055,474)*	*(1,030,691)*	*(1,042,535)*
Wood Biomass and Ethanol Consumption[b]	*218,637*	*228,614*	*233,665*	*241,128*	*252,097*	*244,078*	*266,110*
International Bunker Fuels[b]	*111,828*	*109,750*	*128,384*	*127,618*	*133,704*	*123,127*	*124,702*
CH_4	**31,822**	**30,177**	**30,779**	**31,259**	**31,579**	**31,989**	**31,722**
Natural Gas Systems	9,029	9,452	9,499	9,787	9,904	10,498	10,238
Enteric Fermentation	6,373	6,618	6,731	6,850	6,829	6,788	6,728
Landfills	7,032	5,367	5,320	5,320	5,386	5,295	5,135
Coal Mining	4,003	2,705	2,768	2,754	3,186	3,340	3,458
Manure Management	1,511	2,280	2,303	2,508	2,465	2,416	2,478
Petroleum Systems	1,677	1,390	1,389	1,420	1,427	1,460	1,478
Wastewater Treatment	758	785	794	791	792	787	779
Rice Cultivation	339	326	282	295	343	349	410
Stationary Combustion	355	316	296	311	314	299	303
Abandoned Underground Coal Mines	288	264	261	254	253	244	237
Forest Land Remaining Forest Land	120	388	854	693	419	276	231
Mobile Combustion	223	119	112	105	97	93	93
Composting	15	75	75	79	80	75	75
Petrochemical Production	41	51	48	48	43	39	44
Iron and Steel Production & Metallurgical Coke Production	46	34	35	33	31	17	25
Field Burning of Agricultural Residues	10	8	11	11	11	11	11
Ferroalloy Production	1	+	+	+	+	+	+
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*8*	*7*	*8*	*8*	*8*	*7*	*8*
N_2O	**1,057**	**1,117**	**1,136**	**1,136**	**1,079**	**1,041**	**1,051**
Agricultural Soil Management	683	734	731	733	741	725	722
Mobile Combustion	142	119	108	98	84	77	77

Stationary Combustion	40	67	67	69	68	67	73
Manure Management	48	57	59	60	59	59	59
Nitric Acid Production	56	52	51	61	52	46	54
Wastewater Treatment	11	15	15	16	16	16	16
N2O from Product Uses	14	14	14	14	14	14	14
Forest Land Remaining Forest Land	7	23	48	39	24	16	14
Adipic Acid Production	51	24	29	34	8	9	9
Composting	1	6	6	6	6	6	6
Settlements Remaining Settlements	3	5	5	5	5	5	5
Incineration of Waste	2	1	1	1	1	1	1
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wetlands Remaining Wetlands	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*4*	*4*	*4*	*4*	*4*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances	M	M	M	M	M	M	M
HCFC-22 Production	3	1	1	1	1	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Semiconductor Manufacture	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
SF_6	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Electrical Transmission and Distribution	1	1	1	1	1	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg.

M Mixture of multiple gases

[a] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total. Parentheses indicate negative values or sequestration.

[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.

Emissions of all gases can be summed from each source category into a set of six sectors defined by the Intergovernmental Panel on Climate Change (IPCC). Over the twenty-one-year period of 1990 to 2010, total emissions in the Energy, Industrial Process, and Agriculture sectors grew by 662.1 Tg CO_2 Eq. (12.5 percent), 1.7 Tg (0.6 percent), and 45.0 Tg CO_2 Eq. (11.3 percent), respectively. Emissions decreased in the Waste as well as Solvent and Other Product Use sectors by 35.2 Tg CO_2 Eq. (21.0 percent) and less than 0.1 Tg CO_2 Eq. (0.4 percent), respectively. Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry sector increased by 232.9 Tg CO_2 Eq. (28.8 percent).

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

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

Chapter/IPCC Sector	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Energy	5,287.6	6,297.0	6,203.2	6,304.8	6,126.0	5,756.7	5,949.7
Industrial Processes	313.7	335.1	342.7	356.5	330.8	281.6	315.4
Solvent and Other Product Use	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Agriculture	399.4	439.2	440.9	448.7	450.6	443.7	444.4
Land Use, Land-Use Change, and Forestry (Emissions)	13.8	25.6	43.2	37.6	27.4	20.5	19.0
Waste	167.7	137.2	136.5	136.7	138.2	136.0	132.5
Total Emissions	**6,186.6**	**7,238.3**	**7,170.9**	**7,288.8**	**7,077.4**	**6,643.0**	**6,865.5**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Sinks)[*]	(809.7)	(1,068.8)	(1,118.2)	(1,076.2)	(1,055.5)	(1,030.7)	(1,042.5)
Net Emissions (Sources and Sinks)	**5,376.9**	**6,169.5**	**6,052.7**	**6,212.6**	**6,021.9**	**5,612.3**	**5,823.0**

[*] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total. Please refer to Table 2-9 for a breakout by source.

Note: Totals may not sum due to independent rounding.

Note: 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 2010. In 2010, approximately 85 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 15 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 (50 percent and 15 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: 2010 Energy Chapter Greenhouse Gas Sources

Figure 2-6: 2010 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

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

Gas/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**4,903.9**	**5,939.9**	**5,847.5**	**5,945.7**	**5,759.6**	**5,377.1**	**5,570.9**
Fossil Fuel Combustion	4,742.1	5,757.4	5,666.6	5,771.2	5,579.5	5,214.7	5,406.8
Electricity Generation	1,820.8	2,402.1	2,346.4	2,412.8	2,360.9	2,146.4	2,258.4
Transportation	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5
Industrial	850.1	827.3	861.7	856.5	814.6	743.0	792.1
Residential	338.3	357.9	321.5	342.4	349.3	339.1	349.6
Commercial	219.0	223.5	208.6	219.4	225.1	224.4	228.6
U.S. Territories	27.9	50.0	50.3	46.1	39.8	41.7	41.6
Non-Energy Use of Fuels	115.8	139.6	138.0	130.4	135.0	118.2	119.4

Natural Gas Systems	37.6	30.1	30.1	31.0	32.8	32.2	32.3
Incineration of Waste	8.0	12.5	12.5	12.7	11.9	11.7	12.1
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Biomass - Wood[a]	*214.4*	*205.7*	*202.7*	*202.2*	*197.4*	*181.8*	*191.6*
International Bunker Fuels[b]	*111.8*	*109.7*	*128.4*	*127.6*	*133.7*	*123.1*	*124.7*
Biomass - Ethanol[a]	*4.2*	*22.9*	*31.0*	*38.9*	*54.7*	*62.3*	*74.5*
CH_4	**327.1**	**299.1**	**300.8**	**307.2**	**318.8**	**334.6**	**332.0**
Natural Gas Systems	189.6	198.5	199.5	205.5	208.0	220.5	215.0
Coal Mining	84.1	56.8	58.1	57.8	66.9	70.1	72.6
Petroleum Systems	35.2	29.2	29.2	29.8	30.0	30.7	31.0
Stationary Combustion	7.5	6.6	6.2	6.5	6.6	6.3	6.4
Abandoned Underground Coal Mines	6.0	5.5	5.5	5.3	5.3	5.1	5.0
Mobile Combustion	4.7	2.5	2.3	2.2	2.0	2.0	2.0
Incineration of Waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0
International Bunker Fuels[b]	*0.2*	*0.1*	*0.2*	*0.2*	*0.2*	*0.1*	*0.2*
N_2O	**56.7**	**58.0**	**54.8**	**51.9**	**47.7**	**45.0**	**46.9**
Mobile Combustion	43.9	36.9	33.6	30.3	26.1	23.9	23.9
Stationary Combustion	12.3	20.6	20.8	21.2	21.2	20.8	22.6
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
International Bunker Fuels[b]	*1.1*	*1.0*	*1.2*	*1.2*	*1.2*	*1.1*	*1.1*
Total	**5,287.6**	**6,297.0**	**6,203.2**	**6,304.8**	**6,126.0**	**5,756.7**	**5,949.7**

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, Figure 2-7, and Figure 2-8 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

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

End-Use Sector	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Transportation	**1,489.0**	**1,901.3**	**1,882.6**	**1,899.1**	**1,794.5**	**1,724.6**	**1,741.0**
Combustion	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5
Electricity	3.0	4.7	4.5	5.1	4.7	4.5	4.5

Industrial	**1,536.9**	**1,564.2**	**1,573.7**	**1,571.9**	**1,511.8**	**1,345.0**	**1,429.7**
Combustion	850.1	827.3	861.7	856.5	814.6	743.0	792.1
Electricity	686.8	737.0	712.0	715.4	697.3	602.0	637.6
Residential	**931.4**	**1,214.7**	**1,152.4**	**1,205.9**	**1,192.2**	**1,125.6**	**1,193.0**
Combustion	338.3	357.9	321.5	342.4	349.3	339.1	349.6
Electricity	593.0	856.7	830.8	863.5	842.9	786.5	843.5
Commercial	**757.0**	**1,027.2**	**1,007.6**	**1,048.2**	**1,041.1**	**977.8**	**1,001.5**
Combustion	219.0	223.5	208.6	219.4	225.1	224.4	228.6
Electricity	538.0	803.7	799.0	828.8	816.0	753.5	772.9
U.S. Territories	**27.9**	**50.0**	**50.3**	**46.1**	**39.8**	**41.7**	**41.6**
Total	**4,742.1**	**5,757.4**	**5,666.6**	**5,771.2**	**5,579.5**	**5,214.7**	**5,406.8**
Electricity Generation	**1,820.8**	**2,402.1**	**2,346.4**	**2,412.8**	**2,360.9**	**2,146.4**	**2,258.4**

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.

Figure 2-7: 2010 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Figure 2-8: 2010 End-Use Sector Emissions from Fossil Fuel Combustion

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 36 percent of U.S. energy from fossil fuels and emitted 42 percent of the CO_2 from fossil fuel combustion in 2010. 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 1,741.0 Tg CO_2 Eq. in 2010, or approximately 32 percent of total CO_2 emissions from fossil fuel combustion. The industrial end-use sector accounted for 26 percent of CO_2 emissions from fossil fuel combustion. The residential and commercial end-use sectors accounted for 22 and 19 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 71 and 77 percent of emissions from the residential and commercial end-use sectors, respectively. Significant trends in emissions from energy source categories over the twenty one-year period from 1990 through 2010 included the following:

- Total CO_2 emissions from fossil fuel combustion increased from 4,742.1 Tg CO_2 Eq. to 5,406.8Tg CO_2 Eq.—a 14 percent total increase over the twenty one-year period. From 2009 to 2010, these emissions increased by 192.2 Tg CO_2 Eq. (3.7 percent).
- CO_2 emissions from non-energy use of fossil fuels increased 3.5 Tg CO_2 Eq. (3.0 percent) from 1990 through 2010. Emissions from non-energy uses of fossil fuels were 119.4 Tg CO_2 Eq. in 2010, which constituted 1.7 percent of total national CO_2 emissions.
- CO_2 emissions from incineration of waste (12.1 Tg CO_2 Eq. in 2010) increased by 4.1 Tg CO_2 Eq. (50.9 percent) from 1990 through 2010, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.
- N_2O emissions from stationary combustion increased 10.4 Tg CO_2 Eq. (84.6 percent) from 1990 through 2010. 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.
- CH_4 emissions from coal mining were 72.6 Tg CO_2 Eq. in 2010, a decline in emissions of 11.5 Tg CO_2 Eq. (13.6 percent) from 1990. This occurred as a result of the mining of less gassy coal from underground mines and the increased use of CH_4 collected from degasification systems.
- CH_4 emissions from natural gas systems were 215.0 Tg CO_2 Eq. in 2010; emissions have increased by 25.4Tg CO_2 Eq. (13.4 percent) since 1990.

- In 2010, N_2O emissions from mobile combustion were 23.9 Tg CO_2 Eq. (approximately 7.3 percent of U.S. N_2O emissions). From 1990 to 2010, N_2O emissions from mobile combustion decreased by 45.6 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced NO_x emissions while increasing N_2O emissions. Since 1998, newer control technologies have led to a steady decline in N_2O from this source.

Industrial Processes

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, limestone and dolomite use (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, and zinc production (see Figure 2-9). Industrial processes also release HFCs, PFCs and SF_6. In addition to their use as ODS substitutes, HFCs, PFCs, SF_6, 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.

Figure 2-9: 2010 Industrial Processes Chapter Greenhouse Gas Sources

Table 2-6: Emissions from Industrial Processes (Tg CO_2 Eq.)

Gas/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**188.5**	**165.4**	**169.9**	**172.6**	**159.5**	**118.1**	**139.5**
Iron and Steel Production & Metallurgical Coke Production	99.6	66.0	68.9	71.1	66.1	42.1	54.3
Iron and Steel Production	*97.1*	*64.0*	*66.9*	*69.1*	*63.8*	*41.2*	*52.2*
Metallurgical Coke Production	*2.5*	*2.0*	*1.9*	*2.1*	*2.3*	*1.0*	*2.1*
Cement Production	33.3	45.2	45.8	44.5	40.5	29.0	30.5
Lime Production	11.5	14.4	15.1	14.6	14.3	11.2	13.2
Limestone and Dolomite Use	5.1	6.8	8.0	7.7	6.3	7.6	10.0
Ammonia Production	13.0	9.2	8.8	9.1	7.9	7.9	8.7
Urea Consumption for Non-Agriculture Purposes	3.8	3.7	3.5	4.9	4.1	3.4	4.4
Soda Ash Production and Consumption	4.1	4.2	4.2	4.1	4.1	3.6	3.7
Petrochemical Production	3.3	4.2	3.8	3.9	3.4	2.7	3.3
Aluminum Production	6.8	4.1	3.8	4.3	4.5	3.0	3.0
Carbon Dioxide Consumption	1.4	1.3	1.7	1.9	1.8	1.8	2.2
Titanium Dioxide Production	1.2	1.8	1.8	1.9	1.8	1.6	1.9
Ferroalloy Production	2.2	1.4	1.5	1.6	1.6	1.5	1.5
Zinc Production	0.6	1.0	1.0	1.0	1.2	0.9	1.2
Phosphoric Acid Production	1.5	1.4	1.2	1.2	1.2	1.0	1.0
Lead Production	0.5	0.6	0.6	0.6	0.6	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.1	0.2
CH_4	**1.9**	**1.8**	**1.7**	**1.7**	**1.6**	**1.2**	**1.5**
Petrochemical Production	0.9	1.1	1.0	1.0	0.9	0.8	0.9

Iron and Steel Production & Metallurgical Coke Production	1.0	0.7	0.7	0.7	0.6	0.4	0.5
Iron and Steel Production	1.0	0.7	0.7	0.7	0.6	0.4	0.5
Metallurgical Coke Production	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
N_2O	**33.1**	**23.6**	**24.8**	**29.6**	**18.7**	**17.1**	**19.5**
Nitric Acid Production	17.4	16.2	15.9	18.9	16.1	14.3	16.7
Adipic Acid Production	15.8	7.4	8.9	10.7	2.6	2.8	2.8
HFCs	**36.9**	**120.2**	**123.4**	**129.5**	**129.4**	**125.7**	**135.4**
Substitution of Ozone Depleting Substances[a]	0.3	104.2	109.3	112.3	115.5	120.0	129.7
HCFC-22 Production	36.4	15.8	13.8	17.0	13.6	5.4	5.4
Semiconductor Manufacture	0.17	0.2	0.3	0.3	0.3	0.3	0.3
PFCs	**20.6**	**6.2**	**6.0**	**7.5**	**6.7**	**5.6**	**5.6**
Semiconductor Manufacture	2.2	3.2	3.5	3.7	4.0	4.0	4.0
Aluminum Production	18.4	3.0	2.5	3.8	2.7	1.6	1.6
SF_6	**32.6**	**17.8**	**16.8**	**15.6**	**15.0**	**13.9**	**13.8**
Electrical Transmission and Distribution	26.7	13.9	13.0	12.2	12.2	11.8	11.8
Magnesium Production and Processing	5.4	2.9	2.9	2.6	1.9	1.1	1.1
Semiconductor Manufacture	0.5	1.0	1.0	0.8	0.9	1.0	1.0
Total	**313.7**	**335.1**	**342.7**	**356.5**	**330.8**	**281.6**	**315.4**

+ Does not exceed 0.05 Tg 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 Industrial Processes sector increased by 0.6 percent from 1990 to 2010, as emission decreases from some sources have been offset by increases from other sources. Significant trends in emissions from industrial processes source categories over the twenty-one-year period from 1990 through 2010 included the following:

- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production increased by 29 percent to 54.8 Tg CO_2 Eq. from 2009 to 2010, and have declined overall by 45.8 Tg CO_2 Eq. (45.5 percent) from 1990 through 2010, due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- CO_2 emissions from ammonia production (8.7 Tg CO_2 Eq. in 2010) decreased by 4.4Tg CO_2 Eq. (33.5 percent) since 1990. This is due to a decrease in domestic ammonia production primarily attributed to market fluctuations. Urea consumption for non-agricultural purposes (4.4 Tg CO_2 Eq. in 2010) increased by 0.6Tg CO_2 Eq. (15.3 percent) since 1990.
- N_2O emissions from adipic acid production were 2.8 Tg CO_2 Eq. in 2010, and have decreased significantly in recent years from the widespread installation of pollution control measures. Emissions from adipic acid production have decreased by 82.2 percent since 1990 and by 84.1 percent since a peak in 1995.
- HFC emissions from ODS substitutes have been increasing from small amounts in 1990 to 129.7 Tg CO_2 Eq. in 2010. This increase results from 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 accelerate over the next decade as HCFCs—which are interim substitutes in many applications—are phased out under the provisions of the Copenhagen Amendments to the Montreal Protocol.
- PFC emissions from aluminum production decreased by about 91.5 percent (16.9 Tg CO_2 Eq.) from 1990 to 2010, due to both industry emission reduction efforts and lower domestic aluminum production.

Solvent and Other Product Use

Greenhouse gas emissions are produced as a by-product of various solvent and other product uses. In the United States, N_2O Emissions from Product Uses, the only source of greenhouse gas emissions from this sector, accounted for 4.4 Tg CO_2 Eq., or less than 0.1 percent of total U.S. greenhouse gas emissions in 2010 (see Table 2-7).

Table 2-7: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq.)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
N_2O	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**
N_2O from Product Uses	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Total	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**

In 2010, N_2O emissions from product uses constituted 1.3 percent of U.S. N_2O emissions. From 1990 to 2010, emissions from this source category decreased by just under 0.4 percent, though slight increases occurred in intermediate years.

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 2010, agricultural activities were responsible for emissions of 444.4 Tg CO_2 Eq., or 6.5 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 21.2 percent and 7.8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2010. Agricultural soil management activities, such as fertilizer application and other cropping practices, were the largest source of U.S. N_2O emissions in 2010, accounting for 68.7 percent.

Figure 2-10: 2010 Agriculture Chapter Greenhouse Gas Sources

Table 2-8: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**172.9**	**193.9**	**195.9**	**202.9**	**202.6**	**200.8**	**202.2**
Enteric Fermentation	133.8	139.0	141.4	143.8	143.4	142.6	141.3
Manure Management	31.7	47.9	48.4	52.7	51.8	50.7	52.0
Rice Cultivation	7.1	6.8	5.9	6.2	7.2	7.3	8.6
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**226.5**	**245.3**	**245.1**	**245.8**	**248.0**	**242.9**	**242.3**
Agricultural Soil Management	211.7	227.7	226.6	227.2	229.7	224.6	223.8
Manure Management	14.8	17.6	18.4	18.5	18.3	18.2	18.3
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**399.4**	**439.2**	**440.9**	**448.7**	**450.6**	**443.7**	**444.4**

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 68.7 percent of N_2O emissions in the United States in 2010.

Estimated emissions from this source in 2010 were 223.8 Tg CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2010, although overall emissions were 5.8 percent higher in 2010 than in 1990. Nitrous oxide emissions from this source have not shown any significant long-term trend, as their estimation is highly sensitive to the amount of N applied to soils, which has not changed significantly over the time-period, and to weather patterns and crop type.

- Enteric fermentation was the largest source of CH_4 emissions in 2010, at 141.3 Tg CO_2 Eq. Generally, emissions decreased from 1995 to 2003, though with a slight increase in 2002. This trend was mainly due to decreasing populations of both beef and dairy cattle and increased digestibility of feed for feedlot cattle. Emissions increased from 2004 through 2007, as both dairy and beef populations increased and the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again in 2008, 2009, and 2010 as beef cattle populations decreased. During the timeframe of this analysis, populations of sheep have decreased 51 percent since 1990 while horse populations have increased over 87 percent, mostly since 1999. Goat and swine populations have increased 25 percent and 20 percent, respectively, during this timeframe.
- Overall, emissions from manure management increased 51.2 percent between 1990 and 2010. This encompassed an increase of 64 percent for CH_4, from 31.7 Tg CO_2 Eq. in 1990 to 52 Tg CO_2 Eq. in 2010; and an increase of 23.7 percent for N_2O, from 14.8 Tg CO_2 Eq. in 1990 to 18.3 Tg CO_2 Eq. in 2010. 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.

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 an uptake (sequestration) of carbon in the United States, which offset about 15 percent of total U.S. greenhouse gas emissions in 2010. Forests (including vegetation, soils, and harvested wood) accounted for approximately 88 percent of total 2010 net CO_2 flux, urban trees accounted for 9 percent, mineral and organic soil carbon stock changes accounted for 1 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total net flux in 2010. 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 5.9 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 2010 resulted in a net C sequestration of 1,042.5 Tg CO_2 Eq. (284.3 Tg C) (Table 2-9). This represents an offset of approximately 18 percent of total U.S. CO_2 emissions, or 15 percent of total greenhouse gas emissions in 2010. Between 1990 and 2010, total land use, land-use change, and forestry net C flux resulted in a 28.8 percent increase in CO_2 sequestration.

Table 2-9: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Forest Land Remaining Forest Land	(701.4)		(940.9)	(963.5)	(959.2)	(938.3)	(910.6)	(921.8)
Cropland Remaining Cropland	(35.4)		(18.9)	(19.8)	(20.3)	(18.7)	(18.1)	(16.3)
Land Converted to Cropland	34.3		20.1	20.3	20.0	20.0	20.0	20.0
Grassland Remaining Grassland	(19.7)		(18.0)	(42.2)	(2.9)	(2.8)	(2.6)	(2.4)
Land Converted to Grassland	(6.3)		(11.7)	(12.2)	(10.9)	(10.8)	(10.7)	(10.7)
Settlements Remaining Settlements	(57.1)		(87.8)	(89.8)	(91.9)	(93.9)	(95.9)	(98.0)
Other (Landfilled Yard Trimmings and Food Scraps)	(24.2)		(11.6)	(11.0)	(10.9)	(10.9)	(12.7)	(13.3)

Total	**(809.7)**	**(1,068.8)**	**(1,118.2)**	**(1,076.2)**	**(1,055.5)**	**(1,030.7)**	**(1,042.5)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Land use, land-use change, and forestry source categories also resulted in emissions of CO_2, CH_4, and N_2O that are not included in the net CO_2 flux estimates presented in Table 2-9. The application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization resulted in CO_2 emissions of 7.4 Tg CO_2 Eq. in 2010, an increase of about 4.3 percent relative to 1990. Lands undergoing peat extraction resulted in CO_2 emissions of 1.0 Tg CO_2 Eq. (983 Gg), and N_2O emissions of less than 0.05 Tg CO_2 Eq. N_2O emissions from the application of synthetic fertilizers to forest soils have increased from 0.1 Tg CO_2 Eq. in 1990 to 0.4 Tg CO_2 Eq. in 2010. Settlement soils in 2010 resulted in direct N_2O emissions of 1.5 Tg CO_2 Eq., a 50 percent increase relative to 1990. Emissions from forest fires in 2010 resulted in CH_4 emissions of 4.8 Tg CO_2 Eq., and in N_2O emissions of 4.0 Tg CO_2 Eq. (Table 2-10).

Table 2-10: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Source Category	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**8.1**	**8.9**	**8.8**	**9.2**	**9.6**	**8.2**	**8.4**
Cropland Remaining Cropland: Liming of Agricultural Soils & Urea Fertilization	7.1	7.9	7.9	8.2	8.6	7.2	7.4
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.1	0.9	1.0	1.0	1.1	1.0
CH_4	**2.5**	**8.1**	**17.9**	**14.6**	**8.8**	**5.8**	**4.8**
Forest Land Remaining Forest Land: Forest Fires	2.5	8.1	17.9	14.6	8.8	5.8	4.8
N_2O	**3.1**	**8.5**	**16.5**	**13.8**	**9.0**	**6.5**	**5.8**
Forest Land Remaining Forest Land: Forest Fires	2.1	6.6	14.6	11.9	7.2	4.7	4.0
Forest Land Remaining Forest Land: Forest Soils	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Settlements Remaining Settlements: Settlement Soils	1.0	1.5	1.5	1.6	1.5	1.4	1.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total	**13.8**	**25.6**	**43.2**	**37.6**	**27.4**	**20.5**	**19.0**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Other significant trends from 1990 to 2010 in emissions from land use, land-use change, and forestry source categories include:

- Net C sequestration by forest land has increased by approximately 31 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 20 years, although only at an average rate of 0.22 percent per year.
- Net sequestration of C by urban trees has increased by 71.8 percent over the period from 1990 to 2010. 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 45.0 percent since 1990. This is due in part to a decrease in the amount of yard trimmings and food scraps generated. In

addition, the proportion of yard trimmings and food scraps landfilled has decreased, as there has been a significant rise in the number of municipal composting facilities in the United States.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-11). In 2010, landfills were the third largest source of U.S. anthropogenic CH_4 emissions, accounting for 16.7 percent of total U.S. CH_4 emissions.[48] Additionally, wastewater treatment accounts for 2.5 percent of U.S. CH_4 emissions, and 1.6 percent of N_2O emissions. Emissions of CH_4 and N_2O from composting grew from 1990 to 2010, and resulted in emissions of 3.3 Tg CO_2 Eq. in 2010. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-11.

Figure 2-11: 2010 Waste Chapter Greenhouse Gas Sources

Overall, in 2010, waste activities generated emissions of 132.5 Tg CO_2 Eq., or 1.9 percent of total U.S. greenhouse gas emissions.

Table 2-11: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**163.9**	**130.8**	**130.0**	**130.0**	**131.4**	**129.3**	**125.8**
Landfills	147.7	112.7	111.7	111.7	113.1	111.2	107.8
Wastewater Treatment	15.9	16.5	16.7	16.6	16.6	16.5	16.3
Composting	0.3	1.6	1.6	1.7	1.7	1.6	1.6
N_2O	**3.8**	**6.4**	**6.5**	**6.7**	**6.8**	**6.7**	**6.8**
Wastewater Treatment	3.5	4.7	4.8	4.8	4.9	5.0	5.0
Composting	0.4	1.7	1.8	1.8	1.9	1.8	1.7
Total	**167.7**	**137.2**	**136.5**	**136.7**	**138.2**	**136.0**	**132.5**

Note: 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 2010, net CH_4 emissions from landfills decreased by 39.8 Tg CO_2 Eq. (27 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,[49] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.
- Combined CO_2 and CH_4 emissions from composting have generally increased since 1990, from 0.7 Tg CO_2 Eq. to 3.3 Tg CO_2 Eq. in 2010, which represents slightly less than a four-fold increase over the time series.
- From 1990 to 2010, CH_4 and N_2O emissions from wastewater treatment increased by 0.4 Tg CO_2 Eq. (2.7 percent) and 1.6 Tg CO_2 Eq. (46 percent), respectively.

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

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[48] 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.

[49] 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.

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 (34 percent) of U.S. greenhouse gas emissions in 2010. Transportation activities, in aggregate, accounted for the second largest portion (27 percent). Emissions from industry accounted for about 20 percent of U.S. greenhouse gas emissions in 2010. 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 19 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 5.5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 7 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.

CO_2 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 2-12 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 2010.

Figure 2-12: Emissions Allocated to Economic Sectors

Table 2-12: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2010)

Sector/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Percent[a]**
Electric Power Industry	**1,866.2**	**2,448.8**	**2,393.0**	**2,459.1**	**2,405.8**	**2,191.4**	**2,306.5**	**33.6%**
CO_2 from Fossil Fuel Combustion	1,820.8	2,402.1	2,346.4	2,412.8	2,360.9	2,146.4	2,258.4	32.9%
Stationary Combustion – N_2O and CH_4	7.7	16.5	16.7	17.2	17.3	17.2	18.9	0.3%
Electrical Transmission and Distribution	26.7	13.9	13.0	12.2	12.2	11.8	11.8	0.2%
Incineration of Waste	8.5	12.9	12.9	13.1	12.3	12.1	12.4	0.2%
Limestone and Dolomite Use	2.6	3.4	4.0	3.9	3.1	3.8	5.0	0.1%
Transportation	**1,545.2**	**2,017.4**	**1,994.4**	**2,003.8**	**1,890.6**	**1,812.9**	**1,828.4**	**26.6%**
CO_2 from Fossil Fuel Combustion	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5	25.3%
Substitution of Ozone Depleting Substances	+	72.9	72.2	68.8	64.9	60.2	58.4	0.9%
Mobile Combustion	47.4	37.7	34.2	30.7	26.4	24.0	24.0	0.3%
Non-Energy Use of Fuels	11.8	10.2	9.9	10.2	9.5	8.5	9.5	0.1%
Industry	**1,564.5**	**1,452.5**	**1,488.5**	**1,497.2**	**1,448.0**	**1,327.5**	**1,400.1**	20.4%
CO_2 from Fossil Fuel Combustion	819.1	780.5	812.6	808.0	769.1	696.4	745.5	10.9%
Natural Gas Systems	227.2	228.6	229.6	236.6	240.8	252.6	247.3	3.6%
Non-Energy Use of Fuels	98.3	121.3	119.3	113.0	117.1	105.9	106.1	1.5%
Coal Mining	84.1	56.8	58.1	57.8	66.9	70.1	72.6	1.1%
Iron and Steel Production	100.5	66.7	69.6	71.8	66.7	42.5	54.8	0.8%
Petroleum Systems	35.6	29.5	29.5	30.1	30.3	31.0	31.4	0.5%
Cement Production	33.3	45.2	45.8	44.5	40.5	29.0	30.5	0.4%
Nitric Acid Production	17.4	16.2	15.9	18.9	16.1	14.3	16.7	0.2%
Substitution of Ozone Depleting Substances	+	6.4	7.1	7.8	8.5	10.9	13.5	0.2%

Lime Production	11.5	14.4	15.1	14.6	14.3	11.2	13.2	0.2%
Ammonia Production	13.0	9.2	8.8	9.1	7.9	7.9	8.7	0.1%
HCFC-22 Production	36.4	15.8	13.8	17.0	13.6	5.4	5.4	0.1%
Semiconductor Manufacture	2.9	4.4	4.7	4.8	5.1	5.3	5.3	0.1%
Limestone and Dolomite Use	2.6	3.4	4.0	3.9	3.1	3.8	5.0	0.1%
Abandoned Underground Coal Mines	6.0	5.5	5.5	5.3	5.3	5.1	5.0	0.1%
Aluminum Production	25.3	7.1	6.3	8.1	7.2	4.6	4.6	0.1%
N_2O from Product Uses	4.4	4.4	4.4	4.4	4.4	4.4	4.4	0.1%
Urea Consumption for Non-Ag Purposes	3.8	3.7	3.5	4.9	4.1	3.4	4.4	0.1%
Petrochemical Production	4.2	5.3	4.8	4.9	4.3	3.6	4.3	0.1%
Stationary Combustion	4.9	4.7	4.8	4.6	4.3	3.8	4.1	0.1%
Soda Ash Production and Consumption	4.1	4.2	4.2	4.1	4.1	3.6	3.7	0.1%
Adipic Acid Production	15.8	7.4	8.9	10.7	2.6	2.8	2.8	+
Carbon Dioxide Consumption	1.4	1.3	1.7	1.9	1.8	1.8	2.2	+
Titanium Dioxide Production	1.2	1.8	1.8	1.9	1.8	1.6	1.9	+
Ferroalloy Production	2.2	1.4	1.5	1.6	1.6	1.5	1.5	+
Mobile Combustion	0.9	1.3	1.3	1.3	1.3	1.3	1.3	+
Zinc Production	0.6	1.0	1.0	1.0	1.2	0.9	1.2	+
Magnesium Production and Processing	5.4	2.9	2.9	2.6	1.9	1.1	1.1	+
Phosphoric Acid Production	1.5	1.4	1.2	1.2	1.2	1.0	1.0	+
Lead Production	0.5	0.6	0.6	0.6	0.6	0.5	0.5	+
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2	+
Agriculture	**443.6**	**510.6**	**532.2**	**533.8**	**522.5**	**510.1**	**509.2**	**7.4%**
N_2O from Agricultural Soil Management	211.7	227.7	226.6	227.2	229.7	224.6	223.8	3.3%
Enteric Fermentation	133.8	139.0	141.4	143.8	143.4	142.6	141.3	2.1%
Manure Management	46.5	65.5	66.7	71.1	70.0	68.9	70.4	1.0%
CO_2 from Fossil Fuel Combustion	31.04	46.81	49.04	48.44	45.44	46.66	46.7	0.7%
CH_4 and N_2O from Forest Fires	4.6	14.8	32.6	26.4	16.0	10.5	8.8	0.1%
Rice Cultivation	7.1	6.8	5.9	6.2	7.2	7.3	8.6	0.1%
Liming of Agricultural Soils	4.7	4.3	4.2	4.5	5.0	3.7	3.9	0.1%
Urea Fertilization	2.4	3.5	3.7	3.8	3.6	3.5	3.5	0.1%
CO_2 and N_2O from Managed Peatlands	1.0	1.1	0.9	1.0	1.0	1.1	1.0	+
Mobile Combustion	0.3	0.5	0.5	0.5	0.5	0.5	0.5	+
N_2O from Forest Soils	0.1	0.4	0.4	0.4	0.4	0.4	0.4	+
Field Burning of Agricultural Residues	0.3	0.2	0.3	0.3	0.3	0.3	0.3	+
Stationary Combustion	+	+	+	+	+	+	+	+
Commercial	**388.0**	**379.5**	**367.4**	**382.2**	**393.7**	**395.5**	**401.2**	**5.8%**
CO_2 from Fossil Fuel Combustion	219.0	223.5	208.6	219.4	225.1	224.4	228.6	3.3%
Landfills	147.7	112.7	111.7	111.7	113.1	111.2	107.8	1.6%
Substitution of Ozone Depleting Substances	+	17.6	21.1	24.9	29.1	33.7	38.7	0.6%
Wastewater Treatment	15.9	16.5	16.7	16.6	16.6	16.5	16.3	0.2%
Human Sewage	3.5	4.7	4.8	4.8	4.9	5.0	5.0	0.1%
Composting	0.7	3.3	3.3	3.5	3.5	3.3	3.3	+
Stationary Combustion	1.3	1.3	1.2	1.3	1.3	1.3	1.3	+
Residential	**345.4**	**371.3**	**336.1**	**359.1**	**368.4**	**360.1**	**374.7**	**5.5%**
CO_2 from Fossil Fuel Combustion	338.3	357.9	321.5	342.4	349.3	339.1	349.6	5.1%
Substitution of Ozone Depleting Substances	0.3	7.3	8.9	10.7	12.9	15.1	19.1	0.3%
Stationary Combustion	5.7	4.6	4.1	4.5	4.7	4.5	4.5	0.1%
Settlement Soil Fertilization	1.0	1.5	1.5	1.6	1.5	1.4	1.5	+

U.S. Territories	**33.7**	**58.2**	**59.3**	**53.5**	**48.4**	**45.5**	**45.5**	**0.7%**
CO_2 from Fossil Fuel Combustion	27.9	50.0	50.3	46.1	39.8	41.7	41.6	0.6%
Non-Energy Use of Fuels	5.7	8.1	8.8	7.2	8.4	3.7	3.7	0.1%
Stationary Combustion	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+
Total Emissions	**6,186.6**	**7,238.3**	**7,170.9**	**7,288.8**	**7,077.3**	**6,643.0**	**6,865.5**	**100.0%**
Sinks	**(809.7)**	**(1,068.8)**	**(1,118.2)**	**(1,076.2)**	**(1,055.5)**	**(1,030.7)**	**(1,042.5)**	**-15.2%**
CO_2 Flux from Forests[b]	(701.4)	(940.9)	(963.5)	(959.2)	(938.3)	(910.6)	(921.8)	-13.4%
Urban Trees	(57.1)	(87.8)	(89.8)	(91.9)	(93.9)	(95.9)	(98.0)	-1.4%
Landfilled Yard Trimmings and Food Scraps	(24.2)	(11.6)	(11.0)	(10.9)	(10.9)	(12.7)	(13.3)	-0.2%
CO_2 Flux from Agricultural Soil Carbon Stocks	(27.1)	(28.5)	(53.9)	(14.2)	(12.4)	(11.5)	(9.4)	-0.1%
Net Emissions	**5,376.9**	**6,169.5**	**6,052.7**	**6,212.6**	**6,021.9**	**5,612.3**	**5,823.0**	**84.8%**

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

ODS (Ozone Depleting Substances)

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

[a] Percent of total emissions for year 2010.

[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 34 percent of total U.S. greenhouse gas emissions in 2010. Emissions increased by 24 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for generation. Electricity generation-related emissions increased from 2009 to 2010 by 5.3 percent, primarily due to increased CO_2 emissions from fossil fuel combustion. The increase in electricity-related emissions was due to increased economic output and the resulting increase in electricity demand. Electricity-related emissions also increased due to an increase in the carbon intensity of fuels used to generate electricity. This was caused by fuel switching as the price of coal increased only slightly while the price of natural gas increased significantly. The fuel switching from coal to natural gas and the decrease in electricity generation from other energy sources in 2010, which included a 6 percent decline in hydropower generation from the previous year, resulted in an increase in carbon intensity, and in turn, an increase in emissions from electricity generation. The electricity generation sector in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and non-utility power producers. The majority of electricity generated by these entities was through the combustion of coal in boilers to produce high-pressure steam that is passed through a turbine. Table 2-13 provides a detailed summary of emissions from electricity generation-related activities.

Table 2-13: Electricity Generation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Fuel Type or Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**1,831.4**	**2,418.0**	**2,363.0**	**2,429.4**	**2,375.9**	**2,161.9**	**2,275.4**
Fossil Fuel Combustion	1,820.8	2,402.1	2,346.4	2,412.8	2,360.9	2,146.4	2,258.4
Coal	*1,547.6*	*1,983.8*	*1,953.7*	*1,987.3*	*1,959.4*	*1,740.9*	*1,827.3*
Natural Gas	*175.3*	*318.8*	*338.0*	*371.3*	*361.9*	*372.2*	*399.4*
Petroleum	*97.5*	*99.2*	*54.4*	*53.9*	*39.2*	*33.0*	*31.3*
Geothermal	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	8.0	12.5	12.5	12.7	11.9	11.7	12.1
Limestone and Dolomite Use	2.6	3.4	4.0	3.9	3.1	3.8	5.0
CH_4	**0.3**	**0.5**	**0.5**	**0.5**	**0.5**	**0.4**	**0.5**

Stationary Combustion*	0.3	0.5	0.5	0.5	0.5	0.4	0.5
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**7.8**	**16.4**	**16.6**	**17.1**	**17.2**	**17.2**	**18.8**
Stationary Combustion*	7.4	16.0	16.2	16.7	16.8	16.8	18.5
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
SF_6	**26.7**	**13.9**	**13.0**	**12.2**	**12.2**	**11.8**	**11.8**
Electrical Transmission and Distribution	26.7	13.9	13.0	12.2	12.2	11.8	11.8
Total	**1,866.2**	**2,448.8**	**2,393.0**	**2,459.1**	**2,405.8**	**2,191.4**	**2,306.5**

Note: Totals may not sum due to independent rounding.

* Includes only stationary combustion emissions related to the generation of electricity.

\+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.

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 2011 and Duffield 2006). These source categories include CO_2 from Fossil Fuel Combustion, CH_4 and N_2O from Stationary Combustion, Incineration of Waste, Limestone and Dolomite Use, and SF_6 from Electrical Transmission and Distribution Systems. Note that only 50 percent of the Limestone and Dolomite Use emissions were associated with electricity generation and distributed as described; the remainder of Limestone and Dolomite Use emissions were attributed to the industrial processes economic end-use sector.[50]

When emissions from electricity are distributed among these sectors, industry activities account for the largest share of total U.S. greenhouse gas emissions (29.5 percent), followed closely by emissions from transportation (26.7 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 2-14 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 2010.

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

Table 2-14: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.) and Percent of Total in 2010

Sector/Gas	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Percent**[a]
Industry	**2,237.4**	**2,174.3**	**2,187.2**	**2,193.6**	**2,131.0**	**1,916.1**	**2,024.9**	**29.5%**
Direct Emissions	1,564.5	1,452.5	1,488.5	1,497.2	1,448.0	1,327.5	1,400.1	20.4%
CO_2	1,141.2	1,094.3	1,128.2	1,121.2	1,075.7	949.1	1,018.8	14.8%
CH_4	318.5	293.5	295.7	301.9	313.3	329.0	326.6	4.8%
N_2O	41.6	32.3	33.5	38.2	27.2	25.2	27.9	0.4%
HFCs, PFCs, and SF_6	63.2	32.5	31.0	36.0	31.9	24.2	26.8	0.4%
Electricity-Related	672.9	721.8	698.7	696.3	683.0	588.6	624.9	9.1%
CO_2	660.3	712.7	689.9	687.9	674.5	580.6	616.4	9.0%
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+
N_2O	2.8	4.8	4.9	4.8	4.9	4.6	5.1	0.1%

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[50] 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.

SF_6	9.6	4.1	3.8	3.4	3.5	3.2	3.2	+
Transportation	**1,548.3**	**2,022.2**	**1,999.0**	**2,008.9**	**1,895.4**	**1,817.5**	**1,833.0**	**26.7%**
Direct Emissions	1,545.2	2,017.4	1,994.4	2,003.8	1,890.6	1,812.9	1,828.4	26.6%
CO_2	1,497.8	1,906.8	1,888.0	1,904.2	1,799.3	1,728.7	1,746.0	25.4%
CH_4	4.5	2.2	2.0	1.9	1.7	1.6	1.6	+
N_2O	42.95	35.47	32.12	28.77	24.64	22.37	22.37	0.3%
HFCs[b]	+	72.9	72.2	68.8	64.9	60.2	58.4	0.9%
Electricity-Related	3.1	4.8	4.6	5.2	4.8	4.6	4.6	0.1%
CO_2	3.1	4.8	4.6	5.1	4.7	4.5	4.5	0.1%
CH_4	+	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+	+
Commercial	**939.4**	**1,198.9**	**1,182.3**	**1,227.0**	**1,225.2**	**1,164.7**	**1,190.5**	**17.3%**
Direct Emissions	388.0	379.5	367.4	382.2	393.7	395.5	401.2	5.8%
CO_2	219.0	223.5	208.6	219.4	225.1	224.4	228.6	3.3%
CH_4	164.8	131.7	130.8	130.9	132.4	130.3	126.7	1.8%
N_2O	4.2	6.8	6.8	7.0	7.1	7.1	7.1	0.1%
HFCs	+	17.6	21.1	24.9	29.1	33.7	38.7	0.6%
Electricity-Related	551.4	819.3	814.9	844.7	831.6	769.2	789.3	11.5%
CO_2	541.1	809.0	804.7	834.5	821.2	758.9	778.7	11.3%
CH_4	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.3	5.5	5.7	5.9	5.9	6.0	6.4	0.1%
SF_6	7.9	4.7	4.4	4.2	4.2	4.2	4.0	0.1%
Residential	**953.2**	**1,244.6**	**1,183.4**	**1,239.2**	**1,227.3**	**1,163.1**	**1,236.1**	**18.0%**
Direct Emissions	345.4	371.3	336.1	359.1	368.4	360.1	374.7	5.5%
CO_2	338.3	357.9	321.5	342.4	349.3	339.1	349.6	5.1%
CH_4	4.6	3.6	3.3	3.6	3.7	3.6	3.5	0.1%
N_2O	2.1	2.4	2.4	2.5	2.4	2.3	2.4	+
HFCs	0.3	7.3	8.9	10.7	12.9	15.1	19.1	0.3%
Electricity-Related	607.8	873.4	847.4	880.1	858.9	803.0	861.4	12.5%
CO_2	596.5	862.4	836.7	869.4	848.3	792.2	849.8	12.4%
CH_4	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	2.6	5.8	5.9	6.1	6.1	6.3	7.0	0.1%
SF_6	8.7	5.0	4.6	4.4	4.3	4.3	4.4	0.1%
Agriculture	**474.5**	**540.1**	**559.6**	**566.6**	**550.0**	**536.1**	**535.4**	**7.8%**
Direct Emissions	443.6	510.6	532.2	533.8	522.5	510.1	509.2	7.4%
CO_2	39.2	55.7	57.8	57.7	55.1	54.9	55.0	0.8%
CH_4	175.5	202.2	214.0	217.6	211.5	206.8	207.2	3.0%
N_2O	228.9	252.7	260.5	258.5	255.9	248.4	247.0	3.6%
Electricity-Related	31.0	29.5	27.5	32.9	27.5	26.0	26.3	0.4%
CO_2	30.4	29.1	27.1	32.5	27.2	25.7	25.9	0.4%
CH_4	+	+	+	+	+	+	+	+
N_2O	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+
SF_6	0.4	0.2	0.1	0.2	0.1	0.1	0.1	+
U.S. Territories	**33.7**	**58.2**	**59.3**	**53.5**	**48.4**	**45.5**	**45.5**	**0.7%**
Total	**6,186.6**	**7,238.3**	**7,170.9**	**7,288.8**	**7,077.4**	**6,643.0**	**6,865.5**	**100%**

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 Tg CO_2 Eq. or 0.05 percent.

[a] Percent of total emissions for year 2010.

[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 by-product 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, and SF_6 by-product 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. However, the decline in direct emissions has been sharper. 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 – To be updated

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 27 percent of U.S. greenhouse gas emissions in 2010. The largest sources of transportation greenhouse gases in 2010 were passenger cars (35 percent), light duty trucks, which include sport utility vehicles, pickup trucks, and minivans (30 percent), freight trucks (20 percent) and commercial aircraft (6 percent). These figures include direct emissions from fossil fuel combustion, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types. Table 2-15 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals.

From 1990 to 2010, transportation emissions rose by 17 percent due, in large part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 39 percent from 1990 to 2010, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period.

From 2008 to 2009, CO_2 emissions from the transportation end-use sector declined 4 percent. The decrease in emissions can 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. Similarly, increased jet fuel prices were a factor in the 19 percent decrease in commercial aircraft emissions since 2007. From 2009 to 2010, CO_2 emissions from the transportation end-use sector increased by 1 percent as economic activity rebounded slightly in 2010.

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 17 percent from 1990 to 2010. This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 58.4 Tg CO_2 Eq. in 2010, led to an increase in overall emissions from transportation activities of 19 percent.

Although average fuel economy over this period increased slightly due primarily to the retirement of older vehicles, average fuel economy among new vehicles sold annually gradually declined from 1990 to 2004. The decline in new vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light duty trucks, which grew from about one-fifth of new vehicle sales in the 1970s to slightly over half of the market by 2004. Increasing fuel prices have since decreased the momentum of light duty truck sales, and average new vehicle fuel economy has improved since 2005 as the market share of passenger cars increased. VMT growth among all passenger vehicles has also been impacted, remaining stagnant from 2004 to 2007, compared to an average annual growth rate of 2.5 percent over the period 1990 to 2004. The recession supplemented the effect of increasing fuel prices in 2008 and VMT declined by 2.1 percent, the first decrease in annual passenger vehicle VMT since 1990. Overall, VMT grew by 0.2 percent in 2009. Gasoline fuel consumption increased slightly, while consumption of diesel fuel continued to decrease, due in part to a decrease in commercial activity and freight trucking as a result of the economic recession.

Table 2-15: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Vehicle Type	1990	2005	2006	2007	2008	2009	2010
Passenger Cars	**657.4**	**709.5**	**682.9**	**672.0**	**632.5**	**627.4**	**627.4**
CO_2	629.3	662.3	639.1	632.8	597.9	597.2	597.2
CH_4	2.6	1.1	1.0	0.9	0.8	0.7	0.7
N_2O	25.4	17.8	15.7	13.8	11.7	10.1	10.1
HFCs	+	28.4	27.1	24.6	22.1	19.3	19.3
Light-Duty Trucks	**336.6**	**551.3**	**564.0**	**570.3**	**553.8**	**551.0**	**551.0**
CO_2	321.1	505.9	519.5	528.4	515.1	514.5	514.5
CH_4	1.4	0.7	0.7	0.6	0.6	0.6	0.6
N_2O	14.1	13.7	12.6	11.2	9.5	9.4	9.4
HFCs	+	31.0	31.2	30.1	28.6	26.6	26.6
Medium- and Heavy-Duty Trucks	**231.1**	**408.4**	**418.6**	**425.2**	**403.1**	**365.6**	**365.6**
CO_2	230.1	396.0	406.1	412.5	390.4	353.1	353.1
CH_4	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.8	1.1	1.1	1.1	1.0	0.8	0.8
HFCs	+	11.1	11.4	11.5	11.6	11.6	11.6
Buses	**8.4**	**12.0**	**12.3**	**12.5**	**12.2**	**11.2**	**11.2**
CO_2	8.4	11.8	12.0	12.1	11.8	10.8	10.8
CH_4	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+
HFCs	+	0.2	0.3	0.3	0.4	0.4	0.4
Motorcycles	**1.8**	**1.7**	**1.9**	**2.1**	**2.2**	**2.2**	**2.2**
CO_2	1.7	**1.6**	**1.9**	**2.1**	**2.1**	**2.1**	**2.1**
CH_4	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+
Commercial Aircraft[a]	**136.8**	**162.8**	**138.5**	**139.5**	**123.4**	**112.5**	**112.5**
CO_2	135.4	161.2	137.1	138.1	122.2	111.4	111.4
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	1.3	1.5	1.3	1.3	1.2	1.1	1.1
Other Aircraft[b]	**44.4**	**35.9**	**35.1**	**33.2**	**35.2**	**29.6**	**29.6**
CO_2	43.9	35.5	34.7	32.8	34.8	29.3	29.3
CH_4	0.1	0.1	0.1	0.1	0.1	+	+
N_2O	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Ships and Boats[c]	**45.1**	**45.2**	**48.4**	**55.2**	**37.1**	**30.5**	**30.5**
CO_2	44.5	44.5	47.7	54.4	36.6	30.0	30.0
CH_4	+	+	+	+	+	+	+
N_2O	0.6	0.6	0.7	0.8	0.5	0.4	0.4
HFCs	+	+	+	+	+	+	+
Rail	**39.0**	**53.0**	**55.1**	**54.3**	**50.6**	**43.3**	**43.3**
CO_2	38.5	50.3	52.4	51.6	47.9	40.6	40.6
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.4	0.4	0.4	0.4	0.3	0.3
HFCs	+	2.2	2.2	2.2	2.3	2.3	2.3
Other Emissions from Electricity Generation[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pipelines[e]	**36.0**	**32.2**	**32.3**	**34.3**	**35.7**	**35.2**	**35.2**
CO_2	36.0	32.2	32.3	34.3	35.7	35.2	35.2

Lubricants	**11.8**	**10.2**	**9.9**	**10.2**	**9.5**	**8.5**	**8.5**
CO_2	11.8	10.2	9.9	10.2	9.5	8.5	8.5
Total Transportation	**1,548.3**	**2,022.2**	**1,999.0**	**2,008.9**	**1,895.5**	**1,816.9**	**1,816.9**
International Bunker Fuels[f]	*113.0*	*110.9*	*129.7*	*129.0*	*135.1*	*124.4*	*124.4*

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 8500 lbs; medium- and heavy-duty trucks include vehicles larger than 8500 lbs. HFC emissions primarily reflect HFC-134a.

+ Does not exceed 0.05 Tg 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 data collection problems.

[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 limestone and dolomite use (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 US 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 increasing 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 2010, agricultural soil management was the largest source of N_2O emissions, and enteric fermentation was the second 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 relies less heavily on electricity than the other sectors.

[BEGIN BOX]

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 Limestone and Dolomite Use (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 Substitutes 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 Substitutes 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 Limestone and Dolomite Use (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 Substitutes 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 Substitutes 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.

[END BOX]

[BEGIN BOX]

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 2010; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) emissions per capita.

Table 2-16 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 0.5 percent since 1990. This rate is slightly slower than that for total energy consumption and growth in national population since 1990 and much slower than that for electricity consumption and overall gross domestic product, respectively. Total U.S. greenhouse gas emissions are growing at a rate similar to that of fossil fuel consumption since 1990 (see Table 2-16).

Table 2-16: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Growth Rate**[a]
GDP[b]	100	157	161	165	164	158	163	2.5%
Electricity Consumption[c]	100	134	135	137	136	131	137	1.6%
Fossil Fuel Consumption[c]	100	119	117	119	116	109	113	0.6%
Energy Consumption[c]	100	119	119	121	119	113	118	0.8%
Population[d]	100	118	120	121	122	123	123	1.1%
Greenhouse Gas Emissions[e]	100	117	116	118	114	107	111	0.5%

[a] Average annual growth rate

[b] Gross Domestic Product in chained 2005 dollars (BEA 2011)

[c] Energy-content-weighted values (EIA 2011)

[d] U.S. Census Bureau (2011)

[e] GWP-weighted values

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

Source: BEA (2011), U.S. Census Bureau (2011), and emission estimates in this report.

[END BOX]

2.2. Indirect Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)- TO BE UPDATED

The reporting requirements of the UNFCCC[51] 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.

Since 1970, the United States has published estimates of annual emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2010, EPA 2009),[52] which are regulated under the Clean Air Act. Table 2-17 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 2-17: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	2000	2005	2006	2007	2008	2009
NO_x	**21,707**	**19,116**	**15,900**	**15,039**	**14,380**	**13,547**	**11,468**
Mobile Fossil Fuel Combustion	10,862	10,199	9,012	8,488	7,965	7,441	6,206
Stationary Fossil Fuel Combustion	10,023	8,053	5,858	5,545	5,432	5,148	4,159
Industrial Processes	591	626	569	553	537	520	568
Oil and Gas Activities	139	111	321	319	318	318	393
Incineration of Waste	82	114	129	121	114	106	128
Agricultural Burning	8	8	6	7	8	8	8
Solvent Use	1	3	3	4	4	4	3
Waste	0	2	2	2	2	2	2
CO	**130,038**	**92,243**	**70,809**	**67,238**	**63,625**	**60,039**	**51,452**
Mobile Fossil Fuel	119,360	83,559	62,692	58,972	55,253	51,533	43,355

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[51] See <http://unfccc.int/resource/docs/cop8/08.pdf>.

[52] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2009) and EPA (2010).

Combustion							
Stationary Fossil Fuel Combustion	5,000	4,340	4,649	4,695	4,744	4,792	4,543
Industrial Processes	4,125	2,216	1,555	1,597	1,640	1,682	1,549
Incineration of Waste	978	1,670	1,403	1,412	1,421	1,430	1,403
Agricultural Burning	268	259	184	233	237	270	247
Oil and Gas Activities	302	146	318	319	320	322	345
Waste	1	8	7	7	7	7	7
Solvent Use	5	45	2	2	2	2	2
NMVOCs	**20,930**	**15,227**	**13,761**	**13,594**	**13,423**	**13,254**	**9,313**
Mobile Fossil Fuel Combustion	10,932	7,229	6,330	6,037	5,742	5,447	4,151
Solvent Use	5,216	4,384	3,851	3,846	3,839	3,834	2,583
Industrial Processes	2,422	1,773	1,997	1,933	1,869	1,804	1,322
Stationary Fossil Fuel Combustion	912	1,077	716	918	1,120	1,321	424
Oil and Gas Activities	554	388	510	510	509	509	599
Incineration of Waste	222	257	241	238	234	230	159
Waste	673	119	114	113	111	109	76
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**14,830**	**13,466**	**12,388**	**11,799**	**10,368**	**8,599**
Stationary Fossil Fuel Combustion	18,407	12,849	11,541	10,612	10,172	8,891	7,167
Industrial Processes	1,307	1,031	831	818	807	795	798
Mobile Fossil Fuel Combustion	793	632	889	750	611	472	455
Oil and Gas Activities	390	287	181	182	184	187	154
Incineration of Waste	38	29	24	24	24	23	24
Waste	0	1	1	1	1	1	1
Solvent Use	0	1	0	0	0	0	0
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA

Source: (EPA 2010, EPA 2009) except for estimates from field burning of agricultural residues.
NA (Not Available)
Note: Totals may not sum due to independent rounding.

[BEGIN BOX]

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) 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 83 percent in 2009. 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.

[END BOX]

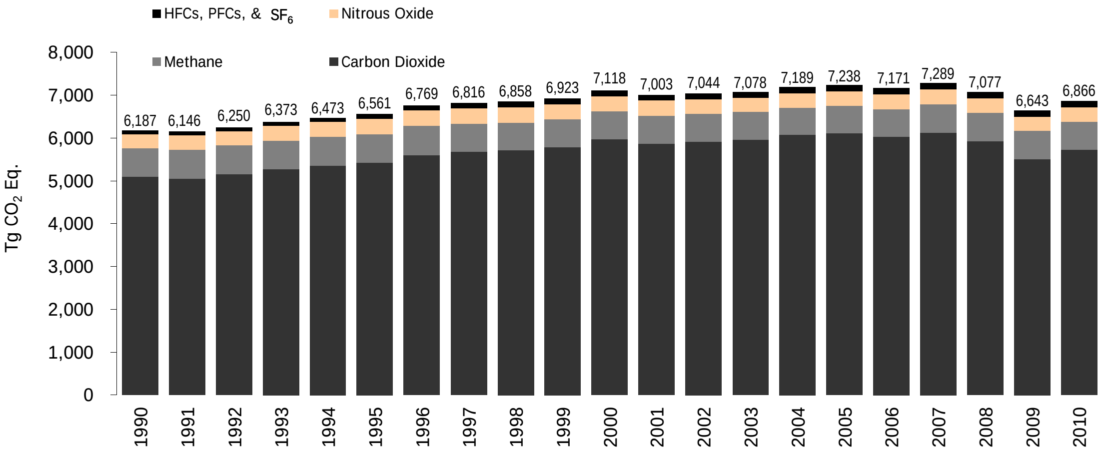

Figure 2-1: U.S. Greenhouse Gas Emissions by Gas

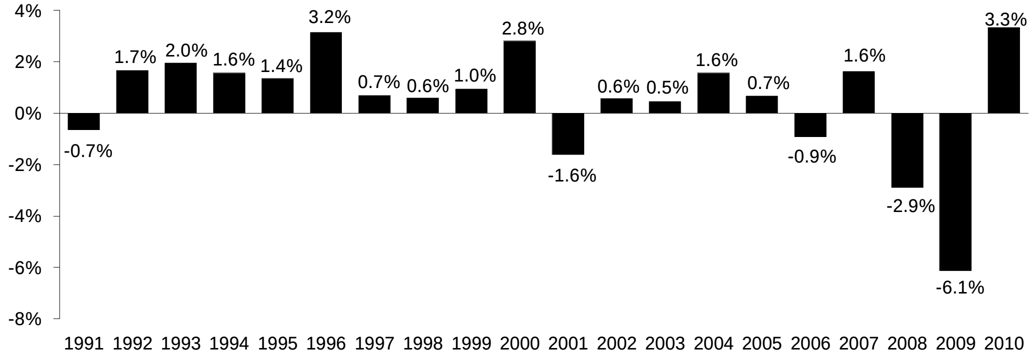

Figure 2-2: Annual Percent Change in U.S. Greenhouse Gas Emissions

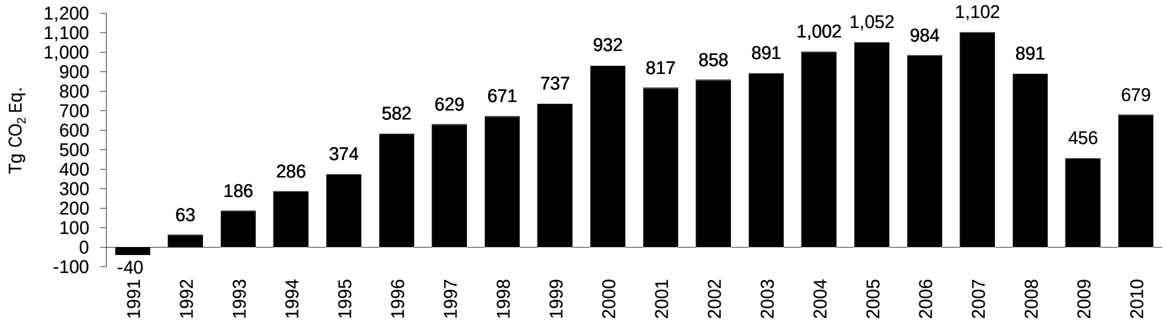

Figure 2-3: Cumulative Change in Annual U.S. Greenhouse Gas Emissions Relative to 1990

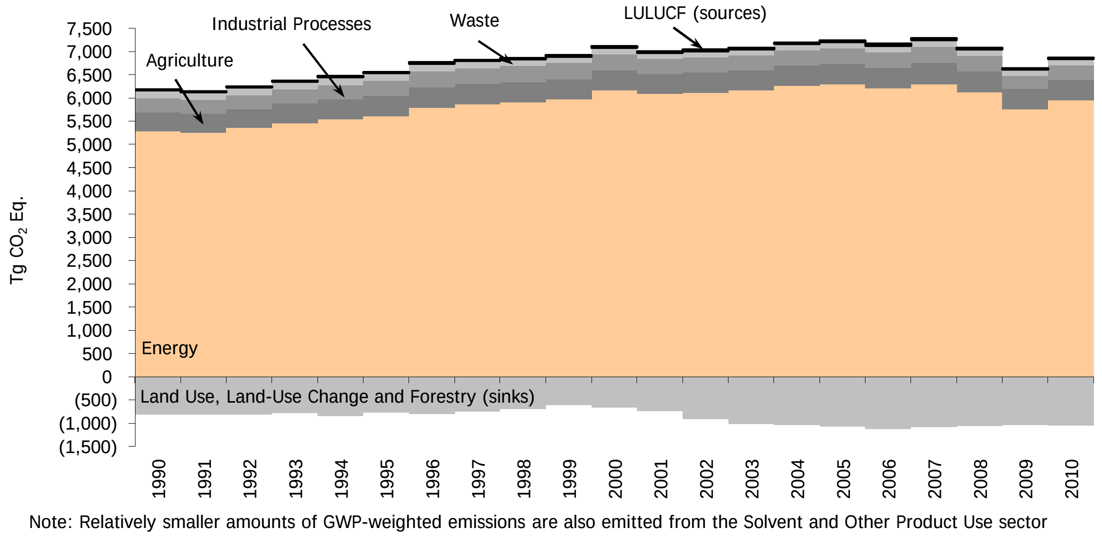

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector

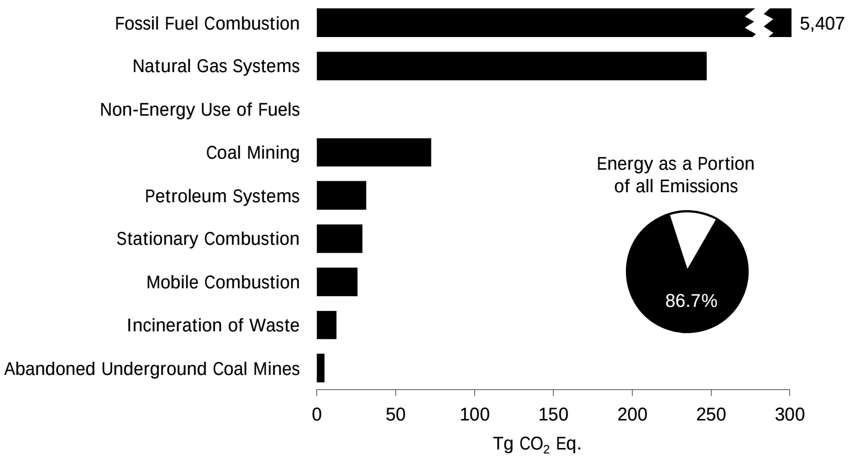

Figure 2-5: 2010 Energy Sector Greenhouse Gas Sources

To be provided:

Figure 2-6: 2010 U.S. Fossil Carbon Flows (Tg CO2 Eq.)

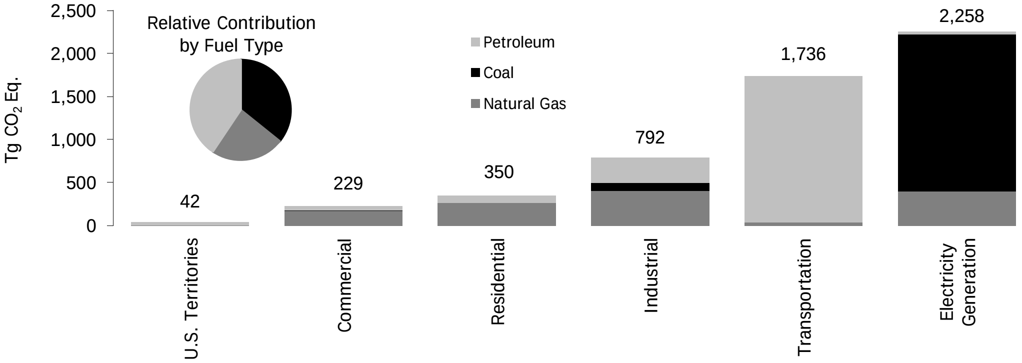

Figure 2-7: 2010 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: Electricity generation also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.

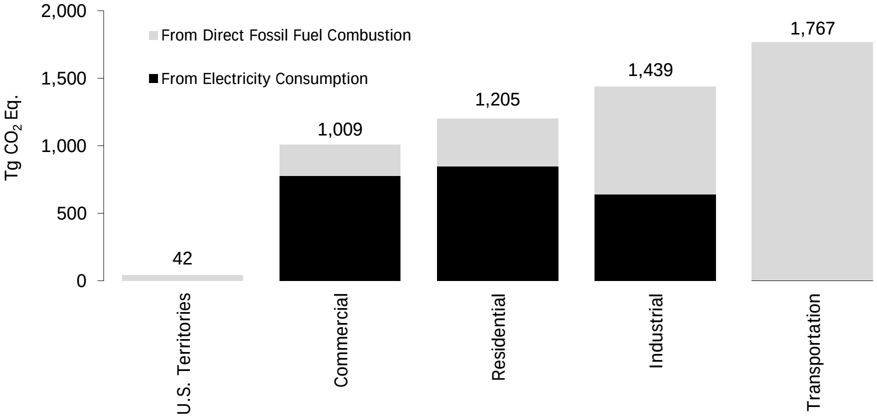

Figure 2-8: 2010 End-Use Sector Emissions from Fossil Fuel Combustion

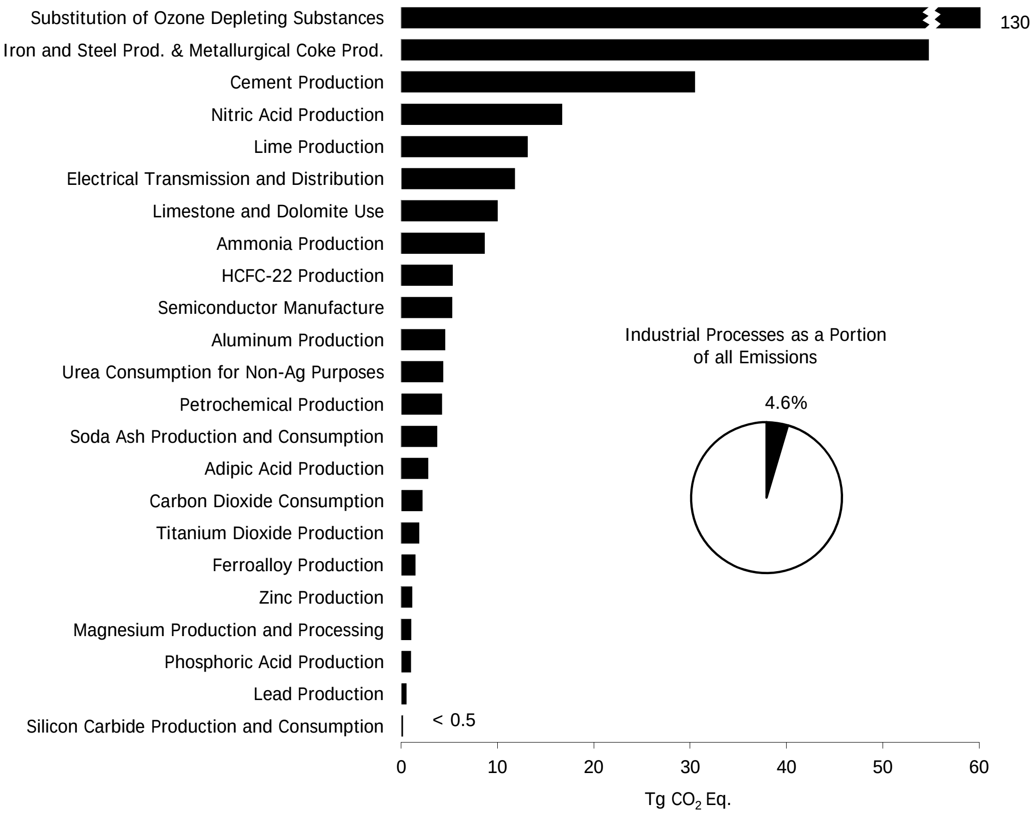

Figure 2-9: 2010 Industrial Processes Chapter Greenhouse Gas Sources

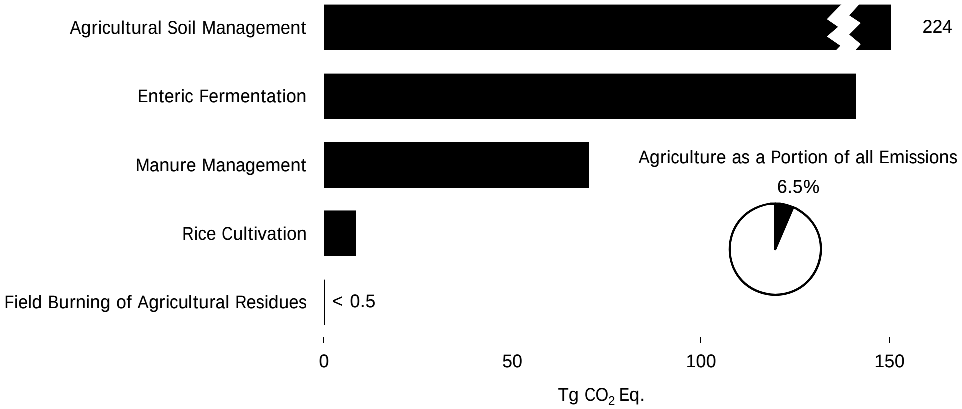

Figure 2-10: 2010 Agriculture Chapter Greenhouse Gas Sources

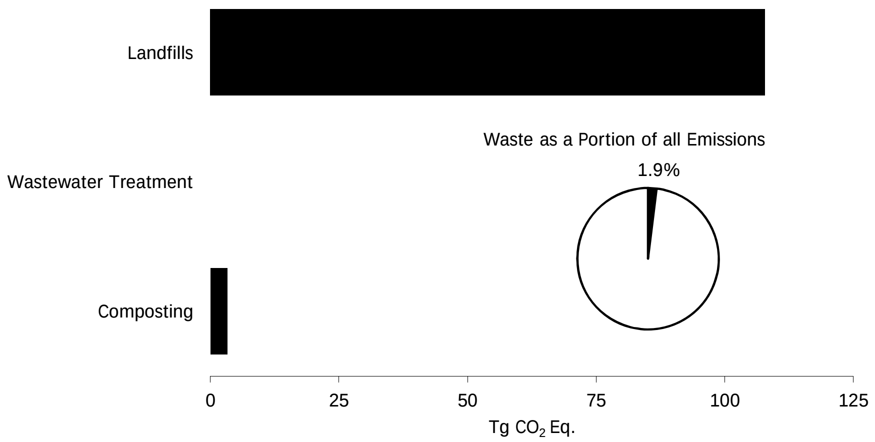

Figure 2-11: 2010 Waste Chapter Greenhouse Gas Sources

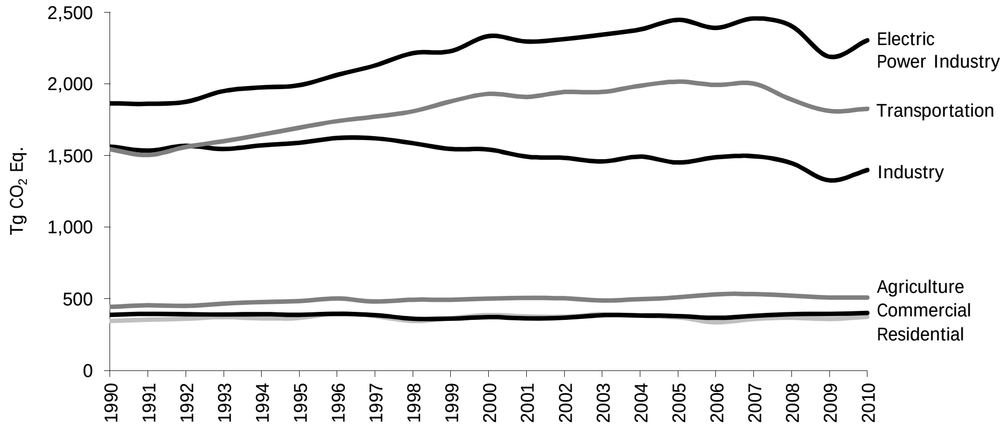

Figure 2-12: Emissions Allocated to Economic Sectors

Note: Does not include U.S. Territories.

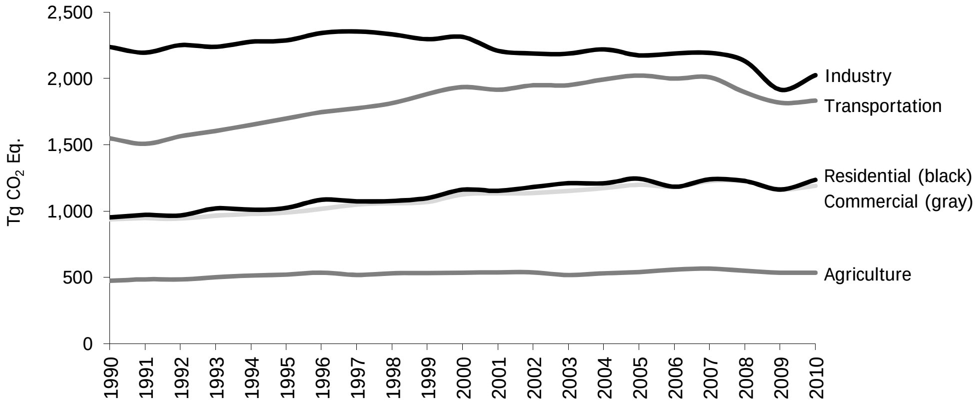

Figure 2-13: Emissions with Electricity Distributed to Economic Sectors

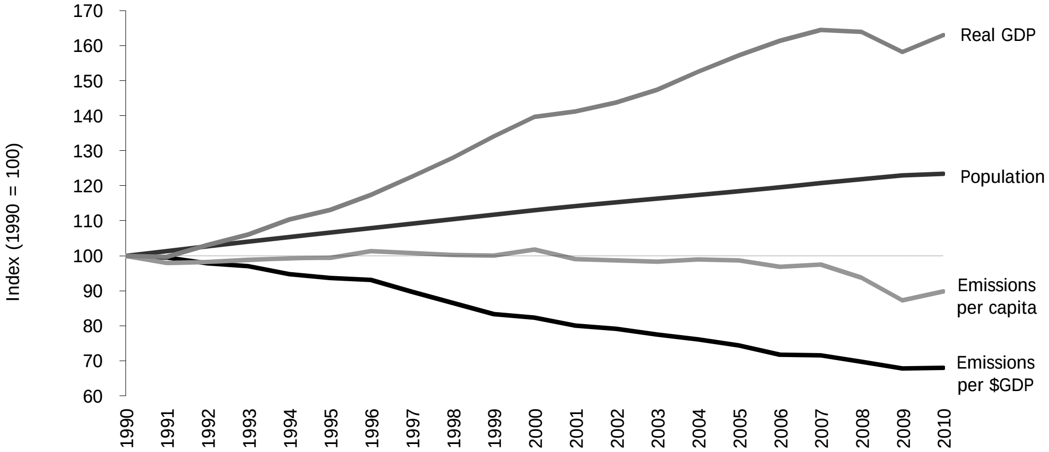

Figure 2-14: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 86.7 percent of total greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis[53] in 2010. This included 97, 50, and 14 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 81 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 (5.5 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 30,313 Tg of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2009, of which the United States accounted for about 18 percent.[54] 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, and mobile fossil fuel combustion was the second largest source of N_2O emissions in the United States.

Figure 3-1: 2010 Energy Chapter Greenhouse Gas Sources

Figure 3-2: 2010 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)

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 teragrams (or million metric tons) of CO_2 equivalents (Tg CO_2 Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 3-2. Overall, emissions due to energy-related activities were 5,949.7 Tg CO_2 Eq. in 2010, an increase of 13 percent since 1990.

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

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CO_2	**4,903.9**	**5,939.9**	**5,847.5**	**5,945.7**	**5,759.6**	**5,377.1**	**5,570.9**
Fossil Fuel Combustion	4,742.1	5,757.4	5,666.6	5,771.2	5,579.5	5,214.7	5,406.8
Electricity Generation	1,820.8	2,402.1	2,346.4	2,412.8	2,360.9	2,146.4	2,258.4
Transportation	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5
Industrial	850.1	827.3	861.7	856.5	814.6	743.0	792.1
Residential	338.3	357.9	321.5	342.4	349.3	339.1	349.6
Commercial	219.0	223.5	208.6	219.4	225.1	224.4	228.6
U.S. Territories	27.9	50.0	50.3	46.1	39.8	41.7	41.6
Non-Energy Use of Fuels	115.8	139.6	138.0	130.4	135.0	118.2	119.4
Natural Gas Systems	37.6	30.1	30.1	31.0	32.8	32.2	32.3
Incineration of Waste	8.0	12.5	12.5	12.7	11.9	11.7	12.1
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3	0.3
*Biomass - Wood**	*214.4*	*205.7*	*202.7*	*202.2*	*197.4*	*181.8*	*191.6*
*International Bunker Fuels**	*111.8*	*109.7*	*128.4*	*127.6*	*133.7*	*123.1*	*124.7*
*Biomass – Ethanol**	*4.2*	*22.9*	*31.0*	*38.9*	*54.7*	*62.3*	*74.5*
CH_4	**327.1**	**299.1**	**300.8**	**307.2**	**318.8**	**334.6**	**332.0**
Natural Gas Systems	189.6	198.5	199.5	205.5	208.0	220.5	215.0
Coal Mining	84.1	56.8	58.1	57.8	66.9	70.1	72.6

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[53] Estimates are presented in units of teragrams of carbon dioxide equivalent (Tg 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.

[54] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Statistics 2010* < http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm> EIA (2010).

Petroleum Systems	35.2	29.2	29.2	29.8	30.0	30.7	31.0
Stationary Combustion	7.5	6.6	6.2	6.5	6.6	6.3	6.4
Abandoned Underground Coal Mines	6.0	5.5	5.5	5.3	5.3	5.1	5.0
Mobile Combustion	4.7	2.5	2.3	2.2	2.0	2.0	2.0
Incineration of Waste	+	+	+	+	+	+	+
*International Bunker Fuels**	*0.2*	*0.1*	*0.2*	*0.2*	*0.2*	*0.1*	*0.2*
N_2O	**56.7**	**58.0**	**54.8**	**51.9**	**47.7**	**45.0**	**46.9**
Mobile Combustion	43.9	36.9	33.6	30.3	26.1	23.9	23.9
Stationary Combustion	12.3	20.6	20.8	21.2	21.2	20.8	22.6
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
*International Bunker Fuels**	*1.1*	*1.0*	*1.2*	*1.2*	*1.2*	*1.1*	*1.1*
Total	**5,287.6**	**6,297.0**	**6,203.2**	**6,304.8**	**6,126.0**	**5,756.7**	**5,949.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

* 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 (Gg)

Gas/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**4,903,883**	**5,939,876**	**5,847,547**	**5,945,683**	**5,759,556**	**5,377,094**	**5,570,891**
Fossil Fuel Combustion	4,742,080	5,757,404	5,666,588	5,771,185	5,579,548	5,214,694	5,406,848
Non-Energy Use of Fuels	115,847	139,559	138,005	130,414	135,012	118,206	119,356
Natural Gas Systems	37,574	30,140	30,118	31,047	32,811	32,165	32,297
Incineration of Waste	7,989	12,468	12,531	12,727	11,888	11,703	12,054
Petroleum Systems	394	305	306	310	297	325	337
*Biomass -Wood**	*214,410*	*205,671*	*202,680*	*202,204*	*197,358*	*181,806*	*191,591*
*International Bunker Fuels**	*111,828*	*109,750*	*128,384*	*127,618*	*133,704*	*123,127*	*124,702*
*Biomass - Ethanol**	*4,227*	*22,943*	*30,985*	*38,924*	*54,739*	*62,272*	*74,519*
CH_4	**15,575**	**14,244**	**14,326**	**14,631**	**15,181**	**15,934**	**15,807**
Natural Gas Systems	9,029	9,452	9,499	9,787	9,904	10,498	10,238
Coal Mining	4,003	2,705	2,768	2,754	3,186	3,340	3,458
Petroleum Systems	1,677	1,390	1,389	1,420	1,427	1,460	1,478
Stationary Combustion	355	316	296	311	314	299	303
Abandoned Underground Coal Mines	288	264	261	254	253	244	237
Mobile Combustion	223	119	112	105	97	93	93
Incineration of Waste	+	+	+	+	+	+	+
*International Bunker Fuels**	*8*	*7*	*8*	*8*	*8*	*7*	*8*
N_2O	**183**	**187**	**177**	**167**	**154**	**145**	**151**
Mobile Combustion	142	119	108	98	84	77	77
Stationary Combustion	40	67	67	69	68	67	73
Incineration of Waste	2	1	1	1	1	1	1
*International Bunker Fuels**	*3*	*3*	*4*	*4*	*4*	*4*	*4*

+ Does not exceed 0.05 Tg CO_2 Eq.

* 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.

[BEGIN BOX]

Box 3 1: 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. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. For calendar year 2010, the first year in which data were reported, facilities in 29 categories provided in 40 CFR part 98 were required to report their 2010 emissions by the September 30, 2011 reporting deadline. Data reporting by affected facilities included the reporting of emissions from fuel combustion at that affected facility.

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. Most methodologies used in the GHGRP are consistent with IPCC, though for the 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 the 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 GHGRP and specific data caveats associated with monitoring methods in the GHGRP has been provided on the GHGRP website.

EPA presents the data collected by the 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.

[END BOX]

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 (Tg CO_2 Eq.)

Gas	1990		2005	2006	2007	2008	2009	2010
CO_2	4,742.1		5,757.4	5,666.6	5,771.2	5,579.5	5,214.7	5,406.8
CH_4	12.1		9.1	8.6	8.8	8.6	8.2	8.3
N_2O	56.2		57.6	54.4	51.5	47.3	44.7	46.6
Total	**4,810.4**		**5,824.1**	**5,729.6**	**5,831.5**	**5,635.5**	**5,267.6**	**5,461.7**

Note: Totals may not sum due to independent rounding.

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

Gas	1990		2005	2006	2007	2008	2009	2010

CO_2	4,742,080	5,757,404	5,666,588	5,771,185	5,579,548	5,214,694	5,406,848
CH_4	579	434	408	417	411	392	396
N_2O	181	186	176	166	153	144	150

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 2010, CO_2 emissions from fossil fuel combustion increased by 3.7 percent relative to the previous year which represents the largest annual increase in CO_2 emissions from fossil fuel combustion for the twenty-one-year period.[55] The increase in CO_2 emissions from fossil fuel combustion was a result of multiple factors including: (1) an increase in economic output resulting in an increase in energy consumption across all sectors; (2) an increase in the carbon intensity of fuels consumed due to only a slight increase in the price of coal, and a significant increase in the price of petroleum and natural gas; and (3) much warmer summer conditions resulting in an increase in electricity demand. In 2010, CO_2 emissions from fossil fuel combustion were 5,406.8 Tg CO_2 Eq., or 14 percent above emissions in 1990 (see Table 3-5).[56]

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

Fuel/Sector	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Coal	**1,718.4**	**2,112.3**	**2,076.6**	**2,106.0**	**2,072.5**	**1,834.4**	**1,933.0**
Residential	3.0	0.8	0.6	0.7	0.7	0.7	0.7
Commercial	12.0	9.3	6.2	6.7	6.5	5.9	5.5
Industrial	155.3	115.3	112.6	107.0	102.6	83.3	96.0
Transportation	NE	NE	NE	NE	NE	NE	NE
Electricity Generation	1,547.6	1,983.8	1,953.7	1,987.3	1,959.4	1,740.9	1,827.3
U.S. Territories	0.6	3.0	3.4	4.3	3.3	3.5	3.5
Natural Gas	**1,001.4**	**1,159.4**	**1,151.1**	**1,228.5**	**1,237.4**	**1,212.8**	**1,278.6**
Residential	238.0	262.2	237.3	257.0	265.5	258.8	267.1
Commercial	142.1	162.9	153.8	164.0	171.1	168.9	172.4
Industrial	409.9	381.2	387.4	399.5	400.5	377.3	402.3
Transportation	36.0	33.1	33.1	35.3	36.7	34.1	36.0
Electricity Generation	175.3	318.8	338.0	371.3	361.9	372.2	399.4
U.S. Territories	NO	1.3	1.4	1.4	1.6	1.5	1.5
Petroleum	**2,021.9**	**2,485.3**	**2,438.6**	**2,436.3**	**2,269.3**	**2,167.1**	**2,194.8**
Residential	97.4	94.9	83.6	84.6	83.1	79.5	81.8
Commercial	64.9	51.3	48.5	48.7	47.4	49.5	50.8
Industrial	284.9	330.7	361.6	349.9	311.4	282.3	293.8
Transportation	1,449.9	1,863.5	1,845.0	1,858.7	1,753.2	1,686.1	1,700.4
Electricity Generation	97.5	99.2	54.4	53.9	39.2	33.0	31.3
U.S. Territories	27.2	45.7	45.5	40.4	35.0	36.7	36.7
Geothermal*	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**4,742.1**	**5,757.4**	**5,666.6**	**5,771.2**	**5,579.5**	**5,214.7**	**5,406.8**

NE (Not estimated)

* 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,

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[55] This increase also represents the largest absolute and percentage increase since 1988 (EIA 2011a).

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

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.[57] 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 2010 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	2006 to 2007		2007 to 2008		2008 to 2009		2009 to 2010		Total 2010
Electricity Generation	Coal	33.6	1.7%	-27.9	-1.4%	-218.5	-11.2%	86.4	5.0%	1,827.3
Electricity Generation	Natural Gas	33.3	9.9%	-9.3	-2.5%	10.3	2.8%	27.2	7.3%	399.4
Electricity Generation	Petroleum	-0.5	-0.9%	-14.7	-27.2%	-6.3	-15.9%	-1.7	-5.2%	31.3
Transportation[a]	Petroleum	13.7	0.7%	-105.6	-5.7%	-67.1	-3.8%	14.4	0.9%	1,700.4
Residential	Natural Gas	19.7	8.3%	8.5	3.3%	-6.8	-2.5%	8.3	3.2%	267.1
Commercial	Natural Gas	10.2	6.6%	7.1	4.3%	-2.2	-1.3%	3.5	2.1%	172.4
Industrial	Coal	-5.6	-5.0%	-4.4	-4.1%	-19.3	-18.8%	12.7	15.2%	96.0
Industrial	Natural Gas	12.1	3.1%	1.0	0.3%	-23.2	-5.8%	25.0	6.6%	402.3
All Sectors[b]	**All Fuels[b]**	**104.6**	**1.8%**	**-191.6**	**-3.3%**	**-364.9**	**-6.5%**	**192.2**	**3.7%**	**5,406.8**

[a] Excludes emissions from International Bunker Fuels.

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

In the United States, 85 percent of the energy consumed in 2010 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[58] (6 percent), primarily hydroelectric power and biofuels (EIA 2011a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 38 percent of total fossil fuel based energy consumption in 2010. Natural gas and coal followed in order of energy demand importance, accounting for approximately 26 and 22 percent of total 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 2011a).

Figure 3-3: 2010 U.S. Energy Consumption by Energy Source

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

Figure 3-5: 2010 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

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,

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

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

including CH_4, CO, and NMVOCs.[59] 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 that all of the C in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

[BEGIN BOX]

Box 3-1: Weather and Non-Fossil Energy Effects on CO_2 from Fossil Fuel Combustion Trends

In 2010, weather conditions remained fairly constant in the winter and much hotter in the summer compared to 2009, as heating degree days decreased slightly (0.7 percent) and cooling degree days increased by 19 percent. This increase in cooling degree days led to an increase in electricity demand to cool homes. Winter conditions were relatively constant in 2010 compared to 2009, and the winter was slightly warmer than normal, with heating degree days in the United States 1.4 percent below normal (see Figure 3-6). Summer conditions were much warmer in 2010 compared to 2009, and summer temperatures were much warmer than normal, with cooling degree days 17 percent above normal (see Figure 3-7) (EIA 2011a).[60]

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1950–2010)

Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950–2010)

Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors[61]) of existing plants in 2010 remained high at just over 91 percent. Electricity output by hydroelectric power plants decreased in 2010 by approximately 6.0 percent. Electricity generated by nuclear plants in 2010 provided more than 3 times as much of the energy consumed in the United States as hydroelectric plants (EIA 2011a). Nuclear, hydroelectric, and wind power capacity factors since 1990 are shown in Figure 3-8.

Figure 3-8: Nuclear, Hydroelectric, and Wind Power Plant Capacity Factors in the United States (1990–2010)

[END BOX]

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.

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

[60] 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 affect 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).

[61] 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 (2011a).

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

End-Use Sector	1990	2005	2006	2007	2008	2009	2010
Electricity Generation	**1,828.5**	**2,418.6**	**2,363.1**	**2,430.0**	**2,378.2**	**2,163.7**	**2,277.3**
CO_2	1,820.8	2,402.1	2,346.4	2,412.8	2,360.9	2,146.4	2,258.4
CH_4	0.3	0.5	0.5	0.5	0.5	0.4	0.5
N_2O	7.4	16.0	16.2	16.7	16.8	16.8	18.5
Transportation	**1,534.6**	**1,936.0**	**1,914.1**	**1,926.5**	**1,818.0**	**1,746.0**	**1,762.3**
CO_2	1,485.9	1,896.6	1,878.1	1,894.0	1,789.8	1,720.1	1,736.5
CH_4	4.7	2.5	2.3	2.2	2.0	2.0	2.0
N_2O	43.9	36.9	33.6	30.3	26.1	23.9	23.9
Industrial	**855.0**	**832.0**	**866.5**	**861.1**	**818.9**	**746.8**	**796.3**
CO_2	850.1	827.3	861.7	856.5	814.6	743.0	792.1
CH_4	1.6	1.5	1.6	1.5	1.4	1.2	1.4
N_2O	3.3	3.2	3.3	3.1	2.9	2.6	2.8
Residential	**344.1**	**362.5**	**325.6**	**346.9**	**354.0**	**343.6**	**354.0**
CO_2	338.3	357.9	321.5	342.4	349.3	339.1	349.6
CH_4	4.6	3.6	3.3	3.6	3.7	3.6	3.5
N_2O	1.1	1.0	0.9	0.9	1.0	0.9	0.9
Commercial	**220.2**	**224.8**	**209.8**	**220.6**	**226.4**	**225.7**	**229.9**
CO_2	219.0	223.5	208.6	219.4	225.1	224.4	228.6
CH_4	0.9	0.9	0.9	0.9	0.9	1.0	0.9
N_2O	0.4	0.4	0.3	0.3	0.3	0.3	0.3
U.S. Territories*	**28.0**	**50.2**	**50.5**	**46.3**	**40.0**	**41.8**	**41.8**
Total	**4,810.4**	**5,824.1**	**5,729.6**	**5,831.5**	**5,635.5**	**5,267.6**	**5,461.7**

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.

* 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.[62] 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. CO 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

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

from transportation.[63] 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 (Tg CO_2 Eq.)

End-Use Sector	1990	2005	2006	2007	2008	2009	2010
Transportation	**1,537.6**	**1,940.8**	**1,918.6**	**1,931.6**	**1,822.7**	**1,750.5**	**1,766.8**
CO_2	1,489.0	1,901.3	1,882.6	1,899.1	1,794.5	1,724.6	1,741.0
CH_4	4.7	2.5	2.4	2.2	2.0	2.0	2.0
N_2O	44.0	37.0	33.6	30.3	26.2	23.9	23.9
Industrial	**1,544.7**	**1,574.0**	**1,583.6**	**1,581.7**	**1,521.3**	**1,353.7**	**1,439.2**
CO_2	1,536.9	1,564.2	1,573.7	1,571.9	1,511.8	1,345.0	1,429.7
CH_4	1.7	1.7	1.7	1.6	1.6	1.4	1.5
N_2O	6.1	8.1	8.2	8.1	7.9	7.3	8.0
Residential	**939.6**	**1,225.1**	**1,162.4**	**1,216.6**	**1,203.1**	**1,136.4**	**1,204.6**
CO_2	931.4	1,214.7	1,152.4	1,205.9	1,192.2	1,125.6	1,193.0
CH_4	4.7	3.8	3.4	3.8	3.9	3.8	3.7
N_2O	3.5	6.7	6.6	6.9	7.0	7.1	7.8
Commercial	**760.5**	**1,034.0**	**1,014.5**	**1,055.3**	**1,048.4**	**985.2**	**1,009.3**
CO_2	757.0	1,027.2	1,007.6	1,048.2	1,041.1	977.8	1,001.5
CH_4	1.0	1.1	1.0	1.1	1.1	1.1	1.1
N_2O	2.6	5.7	5.9	6.1	6.2	6.3	6.7
U.S. Territories*	**28.0**	**50.2**	**50.5**	**46.3**	**40.0**	**41.8**	**41.8**
Total	**4,810.4**	**5,824.1**	**5,729.6**	**5,831.5**	**5,635.5**	**5,267.6**	**5,461.7**

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.

* 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 for 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.[64] 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 (Tg CO_2 Eq.)

Sector/Fuel Type	1990	2005	2006	2007	2008	2009	2010
Electricity Generation	**1,820.8**	**2,402.1**	**2,346.4**	**2,412.8**	**2,360.9**	**2,146.4**	**2,258.4**

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[63] 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.

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

Coal	1,547.6	1,983.8	1,953.7	1,987.3	1,959.4	1,740.9	1,827.3
Natural Gas	175.3	318.8	338.0	371.3	361.9	372.2	399.4
Fuel Oil	97.5	99.2	54.4	53.9	39.2	33.0	31.3
Geothermal	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Industrial	**850.1**	**827.3**	**861.7**	**856.5**	**814.6**	**743.0**	**792.1**
Coal	155.3	115.3	112.6	107.0	102.6	83.3	96.0
Natural Gas	409.9	381.2	387.4	399.5	400.5	377.3	402.3
Fuel Oil	284.9	330.7	361.6	349.9	311.4	282.3	293.8
Commercial	**219.0**	**223.5**	**208.6**	**219.4**	**225.1**	**224.4**	**228.6**
Coal	12.0	9.3	6.2	6.7	6.5	5.9	5.5
Natural Gas	142.1	162.9	153.8	164.0	171.1	168.9	172.4
Fuel Oil	64.9	51.3	48.5	48.7	47.4	49.5	50.8
Residential	**338.3**	**357.9**	**321.5**	**342.4**	**349.3**	**339.1**	**349.6**
Coal	3.0	0.8	0.6	0.7	0.7	0.7	0.7
Natural Gas	238.0	262.2	237.3	257.0	265.5	258.8	267.1
Fuel Oil	97.4	94.9	83.6	84.6	83.1	79.5	81.8
U.S. Territories	**27.9**	**50.0**	**50.3**	**46.1**	**39.8**	**41.7**	**41.6**
Coal	0.6	3.0	3.4	4.3	3.3	3.5	3.5
Natural Gas	NO	1.3	1.4	1.4	1.6	1.5	1.5
Fuel Oil	27.2	45.7	45.5	40.4	35.0	36.7	36.7
Total	**3,256.1**	**3,860.8**	**3,788.5**	**3,877.2**	**3,789.7**	**3,494.5**	**3,670.4**

* U.S. Territories are not apportioned by sector, and emissions are from all fuel combustion sources (stationary and mobile) are presented in this table.

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

Sector/Fuel Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Electricity Generation	**0.3**	**0.5**	**0.5**	**0.5**	**0.5**	**0.4**	**0.5**
Coal	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel Oil	+	+	+	+	+	+	+
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Wood	+	+	+	+	+	+	+
Industrial	**1.6**	**1.5**	**1.6**	**1.5**	**1.4**	**1.2**	**1.4**
Coal	0.3	0.3	0.3	0.2	0.2	0.2	0.2
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Natural Gas	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.9	0.9	1.0	0.9	0.9	0.8	0.9
Commercial	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**1.0**	**0.9**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Wood	0.4	0.5	0.4	0.5	0.5	0.5	0.5
Residential	**4.6**	**3.6**	**3.3**	**3.6**	**3.7**	**3.6**	**3.5**
Coal	0.2	0.1	+	+	+	+	+
Fuel Oil	0.3	0.3	0.3	0.3	0.3	0.2	0.3
Natural Gas	0.4	0.5	0.4	0.5	0.5	0.5	0.5
Wood	3.7	2.8	2.5	2.8	2.9	2.8	2.7
U.S. Territories	**+**	**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
Natural Gas	+	+	+	+	+	+	+
Wood	+	+	+	+	+	+	+
Total	**7.5**	**6.6**	**6.2**	**6.5**	**6.6**	**6.3**	**6.4**

\+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

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

Sector/Fuel Type	1990	2005	2006	2007	2008	2009	2010
Electricity Generation	**7.4**	**16.0**	**16.2**	**16.7**	**16.8**	**16.8**	**18.5**
Coal	6.3	11.6	11.5	11.4	11.6	11.2	12.5
Fuel Oil	0.1	0.1	0.1	0.1	+	+	+
Natural Gas	1.0	4.3	4.7	5.2	5.2	5.6	5.9
Wood	+	+	+	+	+	+	+
Industrial	**3.3**	**3.2**	**3.3**	**3.1**	**2.9**	**2.6**	**2.8**
Coal	0.8	0.6	0.6	0.5	0.5	0.4	0.5
Fuel Oil	0.5	0.5	0.6	0.6	0.5	0.4	0.4
Natural Gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.8	1.9	1.9	1.8	1.7	1.5	1.7
Commercial	**0.4**	**0.4**	**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	**1.1**	**1.0**	**0.9**	**0.9**	**1.0**	**0.9**	**0.9**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.3	0.3	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	0.6	0.5	0.5	0.6	0.6	0.5
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	**12.3**	**20.6**	**20.8**	**21.2**	**21.2**	**20.8**	**22.6**

+ Does not exceed 0.05 Tg 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 39 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 0.8 percent, respectively. Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 42 percent in 2010. Methane and N_2O from electricity generation represented 6 and 40 percent of emissions from CH_4 and N_2O emissions from fossil fuel combustion in 2010, 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).

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,[65] while the other sectors consist of those producers that indicate their primary business is something other than the production of electricity.

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[65] 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).

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 2010 increased approximately 6.3 percent and 1.7 percent, respectively. The trend in the residential and commercial sectors can largely be attributed to warmer, more energy-intensive summer weather conditions compared to 2009. Electricity sales to the industrial sector in 2010 increased approximately 5.0 percent. Overall, in 2010, the amount of electricity generated (in kWh) increased by 4.3 percent from the previous year. This increase was due to an increase in economic output, an increase in the carbon intensity of fuels used to generate electricity due to fuel switching as the price of coal only slightly increased, and the price of petroleum and natural gas increased significantly, and a slight decrease in the contribution of non-fossil fuel sources used to generate electricity. As a result, CO_2 emissions from the electric power sector increased by 5.2 percent as the consumption of coal and natural gas for electricity generation increased by 5.0 percent and 7.3 percent, respectively, in 2010 and the consumption of petroleum for electricity generation, decreased by 5.2 percent.

Industrial Sector

The industrial sector accounted for 15 percent of CO_2 emissions from fossil fuel combustion, 17 percent of CH_4 emissions from fossil fuel combustion, and 6 percent of N_2O emissions from fossil fuel combustion. 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 2011a and EIA 2009c).

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.[66] 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 2009 to 2010, total industrial production and manufacturing output increased by 5.3 and 5.8 percent, respectively (FRB 2011). Over this period, output increased across all production indices for Food, Petroleum Refineries, Chemicals, Paper, Primary Metals, and Nonmetallic Mineral Products (see Figure 3-10).

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

Despite the growth in industrial output (45 percent) and the overall U.S. economy (63 percent) from 1990 to 2010, CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 6.8 percent over that time. 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 2010, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,439.2 Tg CO_2 Eq., or approximately 6.3 percent above 2009 emissions.

Residential and Commercial Sectors

The residential and commercial sectors accounted for 7 and 4 percent of CO_2 emissions from fossil fuel combustion, 43 and 11 percent of CH_4 emissions from fossil fuel combustion, and 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

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[66] 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.

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 2010, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,204.6 Tg CO_2 Eq. and 1,009.3 Tg CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from the residential and commercial sectors increased by 6.0 and 2.4 percent from 2009 to 2010, 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).

Emissions from natural gas consumption represent about 76 and 75 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. In 2010, natural gas CO_2 emissions from the residential and commercial sectors increased by 3.2 percent and 2.1 percent, respectively. The increase in natural gas emissions in both sectors is a result of an increase in energy-intensive weather conditions in the United States compared to 2009.

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 – TO BE UPDATED

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 1,745.5 Tg CO_2 Eq. in 2009, which represented 33 percent of CO_2 emissions, 24 percent of CH_4 emissions, and 65 percent of N_2O emissions from fossil fuel combustion, respectively. Fuel purchased in the U.S. for international aircraft and marine travel accounted for an additional 123.1 Tg CO_2 in 2009; these emissions are recorded as international bunkers and are not included in U.S. totals according to UNFCCC reporting protocols. Among domestic transportation sources, light duty vehicles (including passenger cars and light-duty trucks) represented 64 percent of CO_2 emissions, medium- and heavy-duty trucks 20 percent, commercial aircraft 6 percent, and other sources 9 percent. Light-duty truck CO_2 emissions increased by 60 percent (193.4 Tg) from 1990 to 2009, representing the largest percentage increase of any transportation mode. General aviation aircraft CO_2 emissions also increased by nearly 60 percent (5.7 Tg) from 1990 to 2009. CO_2 from the domestic operation of commercial aircraft decreased by 18 percent (24.0 Tg) from 1990 to 2009. Across all categories of aviation, CO_2 emissions decreased by 21.6 percent (38.7 Tg) between 1990 and 2009. This includes a 59 percent (20.3 Tg) decrease in emissions from domestic military operations. For further information on all greenhouse gas emissions from transportation sources, please refer to Annex 3.2. See Table 3-12 for a detailed breakdown of CO_2 emissions by mode and fuel type.

From 1990 to 2009, transportation emissions rose by 17 percent due, in large part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 39 percent from 1990 to 2009, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period.

From 2008 to 2009, CO_2 emissions from the transportation end-use sector declined 4 percent. The decrease in emissions can 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. Similarly, increased jet fuel prices were a factor in the 19 percent decrease in commercial aircraft emissions since 2007.

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 16 percent from 1990 to 2009. This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 60.2 Tg CO_2 Eq. in 2009, led to an increase in overall emissions from transportation activities of 17 percent.

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 16 percent (235.1 Tg) between 1990 and 2009, an annualized increase of 0.8 percent. The 4 percent decline in emissions between 2008 and 2009 followed the previous year's trend of decreasing emissions. Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil.[67] 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, N_2O, CH_4, and HFCs.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,111.7 Tg in 2009, an increase of 17 percent (161.3 Tg) from 1990. CO_2 emissions from passenger cars and light-duty trucks peaked at 1,184.3 Tg in 2004, and since then have declined about 6 percent. Over the 1990s through early this decade, growth in vehicle travel substantially outweighed improvements in vehicle fuel economy; however, the rate of Vehicle Miles Traveled (VMT) growth slowed considerably starting in 2005 (and declined rapidly in 2008) while average vehicle fuel economy increased. Among new vehicles sold annually, average fuel economy gradually declined from 1990 to 2004 (Figure 3-11), reflecting substantial growth in sales of light-duty trucks—in particular, growth in the market share of sport utility vehicles—relative to passenger cars (Figure 3-12). New vehicle fuel economy improved beginning in 2005, largely due to higher light-duty truck fuel economy standards, which have risen each year since 2005. The overall increase in fuel economy is also due to a slightly lower light-duty truck market share, which peaked in 2004 at 52 percent and declined to 40 percent in 2009.

Figure 3-11: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2008

Figure 3-12: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2008

Light-duty truck[68] CO_2 emissions increased by 60 percent (193.4 Tg) from 1990 to 2009, representing the largest percentage increase of any transportation mode. General aviation aircraft CO_2 emissions also increased by nearly 60 percent (5.7 Tg) from 1990 to 2009. CO_2 from the domestic operation of commercial aircraft decreased by 18 percent (24.0 Tg) from 1990 to 2009. Across all categories of aviation[69], CO_2 emissions decreased by 21.6 percent (38.7 Tg) between 1990 and 2009. This includes a 59 percent (20.3 Tg) decrease in emissions from domestic military operations. For further information on all greenhouse gas emissions from transportation sources, please refer to Annex 3.2.

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

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[67] Biofuel estimates are presented for informational purposes only in the Energy chapter, 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 7). More information and additional analyses on biofuels are available at EPA's "Renewable Fuels: Regulations & Standards" web page: http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm

[68] Includes "light-duty trucks" fueled by gasoline, diesel and LPG.

[69] 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.

Fuel/Vehicle Type	1990	2005	2006	2007	2008	2009	2010
Gasoline	**983.7**	**1,187.8**	**1,178.2**	**1,181.2**	**1,130.3**	**1,125.7**	
Passenger Cars	621.4	658.0	635.0	628.7	594.0	593.3	
Light-Duty Trucks	309.1	478.7	491.5	500.1	486.5	485.9	
Medium- and Heavy-Duty Trucks[b]	38.7	34.9	35.5	36.1	33.7	30.6	
Buses	0.3	0.4	0.4	0.4	0.4	0.3	
Motorcycles	1.7	1.6	1.9	2.1	2.1	2.1	
Recreational Boats	12.4	14.1	14.0	13.9	13.5	13.4	
Distillate Fuel Oil (Diesel)	**262.9**	**451.8**	**470.3**	**476.3**	**443.5**	**402.5**	
Passenger Cars	7.9	4.2	4.1	4.1	3.9	3.9	
Light-Duty Trucks	11.5	25.8	26.8	27.3	26.9	26.7	
Medium- and Heavy-Duty Trucks[b]	190.5	360.6	370.1	376.1	356.0	321.8	
Buses	8.0	10.6	10.8	10.8	10.3	9.3	
Rail	35.5	45.6	47.8	46.6	43.2	36.2	
Recreational Boats	2.0	3.1	3.2	3.3	0.9	3.5	
Ships and Other Boats	7.5	8.1	7.5	8.2	2.2	1.2	
International Bunker Fuels [c]	*11.7*	*9.4*	*8.8*	*8.2*	*9.0*	*8.3*	
Jet Fuel	**176.2**	**194.2**	**169.5**	**168.7**	**155.1**	**138.8**	
Commercial Aircraft	135.4	161.2	137.1	138.1	122.2	111.4	
Military Aircraft	34.4	18.1	16.4	16.1	16.3	14.1	
General Aviation Aircraft	6.4	14.9	16.0	14.5	16.6	13.3	
International Bunker Fuels [c]	*46.4*	*56.7*	*74.6*	*73.8*	*75.5*	*69.4*	
Aviation Gasoline	**3.1**	**2.4**	**2.3**	**2.2**	**2.0**	**1.8**	
General Aviation Aircraft	3.1	2.4	2.3	2.2	2.0	1.8	
Residual Fuel Oil	**22.6**	**19.3**	**23.0**	**29.0**	**19.9**	**12.0**	
Ships and Other Boats[d]	22.6	19.3	23.0	29.0	19.9	12.0	
International Bunker Fuels [c]	*53.7*	*43.6*	*45.0*	*45.6*	*49.2*	*45.4*	
Natural Gas	**36.0**	**33.1**	**33.1**	**35.3**	**36.8**	**36.3**	
Passenger Cars	+	+	+	+	+	+	
Light-Duty Trucks	+	+	+	+	+	+	
Buses	+	0.8	0.8	1.0	1.1	1.1	
Pipeline	36.0	32.2	32.3	34.3	35.7	35.2	
LPG	**1.4**	**1.7**	**1.7**	**1.4**	**2.4**	**2.5**	
Light-Duty Trucks	0.6	1.3	1.2	1.0	1.8	1.8	
Medium- and Heavy-Duty Trucks[b]	0.8	0.4	0.5	0.4	0.7	0.7	
Buses	+	+	+	+	+	+	
Electricity	**3.0**	**4.7**	**4.5**	**5.0**	**4.7**	**4.4**	
Rail	3.0	4.7	4.5	5.0	4.7	4.4	
Total	**1,489.0**	**1,901.3**	**1,882.6**	**1,899.0**	**1,794.6**	**1,724.1**	
Total (Including Bunkers) [c]	**1,600.8**	**2,011.1**	**2,011.0**	**2,026.6**	**1,928.3**	**1,847.2**	

[a] 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.

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

[c] 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.

Note: Totals may not sum due to independent rounding.

Note: See section 3.10 of this chapter, in line with IPCC methodological guidance and UNFCCC reporting obligations, for more information on ethanol.
+ Less than 0.05 Tg CO_2 Eq.
- Unreported or zero

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, which are stationary; 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.). Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-13 and Table 3-14 provide CH_4 and N_2O emission estimates in Tg CO_2 Eq.[70]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.3 percent) but was the second largest source of U.S. N_2O emissions (9 percent). From 1990 to 2009, mobile source CH_4 emissions declined by 58 percent, to 2.0 Tg CO_2 Eq. (93 Gg), 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 46 percent, to 23.9 Tg CO_2 Eq. (77 Gg). Earlier generation control technologies initially resulted in higher N_2O emissions, causing a 26 percent increase in N_2O emissions from mobile sources between 1990 and 1998. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in a 50 percent decrease in mobile source N_2O emissions from 1998 to 2009 (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

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

Fuel Type/Vehicle Type[a]	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**
Gasoline On-Road	**4.2**	**1.9**	**1.7**	**1.6**	**1.4**	**1.3**
Passenger Cars	2.6	1.1	1.0	0.9	0.8	0.7
Light-Duty Trucks	1.4	0.7	0.6	0.6	0.6	0.6
Medium- and Heavy-Duty Trucks and Buses	0.2	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+
Diesel On-Road	**+**	**+**	**+**	**+**	**+**	**+**
Passenger Cars	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Road	**0.4**	**0.6**	**0.6**	**0.5**	**0.5**	**0.5**
Ships and Boats	+	+	+	+	+	+
Rail	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.2	0.2	0.1	0.1	0.1	0.1
Agricultural Equipment[b]	0.1	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[c]	+	0.1	0.1	0.1	0.1	0.1
Other[d]	0.1	0.1	0.1	0.1	0.1	0.1
Total	**4.7**	**2.5**	**2.3**	**2.2**	**2.0**	**2.0**

[a] See Annex 3.2 for definitions of on-road vehicle types.
[b] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

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[70] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2009.

[c] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[d] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
Note: Totals may not sum due to independent rounding.
+ Less than 0.05 Tg CO_2 Eq.

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

Fuel Type/Vehicle Type[a]	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**
Gasoline On-Road	**40.1**	**32.1**	**29.0**	**25.5**	**21.8**	**19.9**
Passenger Cars	25.4	17.7	15.7	13.7	11.7	10.0
Light-Duty Trucks	14.1	13.6	12.5	11.1	9.5	9.3
Medium- and Heavy-Duty Trucks and Buses	0.6	0.8	0.7	0.7	0.6	0.5
Motorcycles	+	+	+	+	+	+
Diesel On-Road	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Passenger Cars	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	0.2	0.3	0.3	0.3	0.3	0.3
Alternative Fuel On-Road	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Non-Road	**3.6**	**4.3**	**4.2**	**4.3**	**3.8**	**3.6**
Ships and Boats	0.6	0.6	0.7	0.8	0.5	0.4
Rail	0.3	0.4	0.4	0.4	0.3	0.3
Aircraft	1.7	1.9	1.6	1.6	1.5	1.3
Agricultural Equipment[b]	0.2	0.4	0.4	0.4	0.4	0.4
Construction/Mining Equipment[c]	0.3	0.5	0.5	0.5	0.5	0.5
Other[d]	0.4	0.6	0.6	0.6	0.6	0.6
Total	**43.9**	**36.9**	**33.6**	**30.3**	**26.1**	**23.9**

[a] See Annex 3.2 for definitions of on-road vehicle types.
[b] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[c] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[d] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
Note: Totals may not sum due to independent rounding.
+ Less than 0.05 Tg 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). 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 Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), primarily from the Monthly Energy Review and published supplemental tables on petroleum product detail (EIA 2011b). The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from Jacobs (2010).[71]

For consistency of reporting, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA on an annual basis and used in this inventory are predominantly from mid-stream or conversion energy consumers such as refiners and electric power generators. These annual surveys are supplemented with end-use energy consumption surveys, such as the Manufacturing Energy Consumption Survey, that are conducted on a periodic basis (every 4 years). These consumption data sets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total. [72]

It is also important to 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).[73]

2. *Subtract uses accounted for in the Industrial Processes 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 chapter, as they were consumed during non-energy related industrial activity. To make these adjustments, additional data were collected from AISI (2004 through 2011), Coffeyville (2011), U.S. Census Bureau (2011), EIA (2011c), USGS (1991 through 2011), USGS (1994 through 2011), USGS (1995, 1998, 2000 through 2002, 2007, 2009 and 2010), USGS (1991 through 2010a), USGS (1991 through 2010b), USGS (2010) and USGS (2011).[74]
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.[75] 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.[76] 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 (2011a), data for synthetic natural gas were collected from EIA (2011c), and data for CO_2 exports were collected from the Dakota Gasification Company (2006), Fitzpatrick (2002), Erickson (2003), and EIA (2007b).
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 the Federal Highway Administration's

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[71] 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 42 Tg CO_2 Eq. in 2010.

[72] 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.

[73] 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.

[74] 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 chapter.

[75] Energy statistics from EIA (2011b) are already adjusted downward to account for ethanol added to motor gasoline, and biogas in natural gas.

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

(FHWA) VMT 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 upward to match the value obtained from the bottom-up analysis based on VMT. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate consumption totals for the residential, commercial, and industrial sectors were adjusted downward proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2009 through 2010), Benson (2002 through 2004), DOE (1993 through 2010), EIA (2009a), EIA (1991 through 2010), EPA (2009), and FHWA (1996 through 2010).[77] The 2010 values used in this allocation were proxied to the 2009 values for the public review version of the Inventory.

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 (2011b).

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).[78] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Energy Support Center (Defense Logistics Agency) of the U.S. Department of Defense (DoD) (DESC 2011) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was obtained from FAA (2006 and 2009); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2011) for 1990 through 2001, 2007 to 2010, 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. The 2010 values used for aviation were proxied to the 2009 values for the public review version of the Inventory.

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 mandatory reporting rule (EPA 2010a). 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

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[77] FHWA data on vehicle miles traveled from the VM-1 table were not available for 2009 due to a delay caused by changes in data collection procedures. Based on data from FHWA's Traffic Volume Trends Program, the overall increase in VMT between 2008 and 2009 was estimated to be 0.2%. Total VMT was distributed among vehicle classes based on trends in fuel consumption by fuel type between 2008 and 2009, as described below.
Fuel use by vehicle class (also in the VM-1 table) was not available from FHWA for 2009, but changes in overall diesel and gasoline consumption were released in Table MF21. Fuel use in vehicle classes that were predominantly gasoline was estimated to grow by the rate of growth for gasoline between 2008 and 2009. Fuel use in vehicle classes that were predominantly diesel was estimated to fall by the same rate that diesel fuel consumption fell overall in 2009. VMT was then distributed to vehicle classes based on these fuel consumption estimates, assuming no relative change in MPG between vehicle classes.

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

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 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.

   - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2010); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2010). Fuel use by vehicle class (found in the VM-1 table) was not available from FHWA for 2009, but changes in overall diesel and gasoline consumption were released in Table MF21. Fuel use in vehicle classes that were predominantly gasoline was estimated to grow by the rate of growth for gasoline between 2008 and 2009. Fuel use in vehicle classes that were predominantly diesel were estimated to fall by the same rate that diesel fuel consumption fell overall in 2009.

   - For non-road vehicles, activity data were obtained from AAR (2009 through 2010), APTA (2007 through 2010), BEA (1991 through 2009), Benson (2002 through 2004), DOE (1993 through 2010), DESC (2011), DOC (1991 through 2010), DOT (1991 through 2010), EIA (2009a), EIA (2009d), EIA (2007a), EIA (2002), EIA (1991 through 2011), EPA (2010b), FAA (2008), and Gaffney (2007).

   - For jet fuel used by aircraft, CO_2 emissions were calculated directly based on reported consumption of fuel as reported by EIA, and allocated to commercial aircraft using flight-specific fuel consumption data from the Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT) (FAA 2011).[79] Allocation to domestic general aviation was made using FAA Aerospace Forecast data, and allocation to domestic military uses was made using DoD data (see Annex 3.7).

Heat contents and densities were obtained from EIA (2010) and USAF (1998).[80]

[BEGIN BOX]

Box 3-2: 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 Tg CO_2 Eq./QBtu for natural gas to upwards of 95 Tg CO_2 Eq./QBtu for coal and petroleum coke.[81] 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

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[79] Data for inventory years 2000 through 2005 were developed using the FAA's System for assessing Aviation's Global Emissions (SAGE) model. That tool has been incorporated into the Aviation Environmental Design Tool (AEDT), which calculates noise in addition to aircraft fuel burn and emissions for all commercial flights globally in a given year. Data for inventory years 2006-2009 were developed using AEDT. The AEDT model dynamically models aircraft performance in space and time to produce fuel burn, emissions and noise. Full flight gate-to-gate analyses are possible for study sizes ranging from a single flight at an airport to scenarios at the regional, national, and global levels. AEDT is currently used by the U.S. government to consider the interdependencies between aircraft-related fuel burn, noise and emissions.

[80] 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 3.7.

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

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 sector was closely related to the C content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 Tg 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 (Tg CO_2 Eq./QBtu)

Sector	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Residential [a]	57.4	56.6	56.5	56.3	56.0	56.0	55.9
Commercial [a]	59.2	57.5	57.2	57.1	56.7	56.9	56.8
Industrial [a]	64.3	64.4	64.4	64.0	63.5	63.0	63.1
Transportation [a]	71.1	71.4	71.6	71.9	71.6	71.5	71.5
Electricity Generation [b]	87.3	85.8	85.4	84.7	84.9	83.7	83.5
U.S. Territories [c]	73.0	73.4	73.5	73.8	73.3	73.1	73.1
All Sectors [c]	**73.0**	**73.5**	**73.5**	**73.3**	**73.0**	**72.4**	**72.4**

[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-one-year period of 1990 through 2010, 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 2010 was approximately 8.0 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 2011).

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 (2011a), EPA (2010a), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

[END BOX]

Uncertainty and Time Series Consistency – TO BE UPDATED

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 for . 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 Tier 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.[82] 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.[83]

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).[84] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte

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[82] 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.

[83] 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.

[84] 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

Carlo Sampling.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-16. Fossil fuel combustion CO_2 emissions in 2009 were estimated to be between 5,149.0 and 5,522.4 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 1 percent below to 6 percent above the 2009 emission estimate of 5,209.0.0 Tg CO_2 Eq.

Table 3-16: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-related Fossil Fuel Combustion by Fuel Type and Sector (Tg CO_2 Eq. and Percent)

Fuel/Sector	**2009 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a]**			
		(Tg CO_2 Eq.)		**(%)**	
		Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Coal [b]	**1,841.0**	**1,779.3**	**2,015.6**	**-3%**	**+9%**
Residential	0.6	0.6	0.7	-6%	+15%
Commercial	5.8	5.5	6.7	-5%	+15%
Industrial	83.4	80.5	97.5	-3%	+17%
Transportation	NE	NE	NE	NA	NA
Electricity Generation	1,747.6	1,680.4	1,915.8	-4%	+10%
U.S. Territories	3.5	3.1	4.2	-12%	+19%
Natural Gas [b]	**1,200.9**	**1,209.4**	**1,276.6**	**+1%**	**+6%**
Residential	257.2	250.0	275.2	-3%	+7%
Commercial	167.9	163.2	179.7	-3%	+7%
Industrial	365.0	374.9	412.7	+3%	+13%
Transportation	36.3	35.2	38.8	-3%	+7%
Electricity Generation	373.1	362.3	392.0	-3%	+5%
U.S. Territories	1.5	1.3	1.7	-12%	+17%
Petroleum [b]	**2,166.7**	**2,067.2**	**2,323.5**	**-5%**	**+7%**
Residential	81.4	76.9	85.7	-6%	+5%
Commercial	50.3	47.9	52.4	-5%	+4%
Industrial	282.0	231.2	330.4	-18%	+17%
Transportation	1,683.4	1,598.6	1,826.8	-5%	+9%
Electric Utilities	32.9	31.5	35.4	-4%	+7%
U.S. Territories	36.7	33.8	40.9	-8%	+11%
Total (excluding Geothermal) [b]	**5,208.6**	**5,148.76**	**5,522.0**	**-1%**	**+6%**
Geothermal	0.4	NE	NE	NE	NE
Total (including Geothermal) [b,c]	**5,209.0**	**5,149.0**	**5,522.4**	**-1%**	**+6%**

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.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2009. Details on the emission trends through time are described in more detail in the Methodology section, above.

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uncertainties are represented in this uncertainty analysis.

QA/QC and Verification – TO BE UPDATED

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 2011a) updated energy consumption statistics across the time series. These revisions primarily impacted the emission estimates for 2008 and 2009; however revisions to industrial petroleum consumption impacted estimates across the time series. Overall, these changes resulted in an average annual increase of 3.3 Tg CO_2 Eq. (less than 0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2009.

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 Greenhouse Gas Reporting Program (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,[85] some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions. In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes 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. 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]

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 this year's Inventory, 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.

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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>

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 Annual Energy Review (EIA 2011a). Fuel consumption data for coal, natural gas, and fuel oil for the United States were obtained from EIA's Monthly Energy Review and unpublished supplemental tables on petroleum product detail (EIA 2011b). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by Jacobs (2010).[87] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[88] Construction and agricultural fuel use was obtained from EPA (2010a). 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

In this year's Inventory, the emission estimation methodology for the electric power sector was revised from Tier 1 to Tier 2 as fuel consumption for the electricity generation sector by control-technology type was obtained from EPA's Acid Rain Program Dataset (EPA 2011). This combustion technology- and fuel-use data was available by facility from 1996 to 2010.

Since there was a difference between the EPA (2011) and EIA (2011a) total energy consumption estimates, the remainder between total energy consumption using EPA (2011) and EIA (2011a) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2010.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2011) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2011a) and the ratio of combustion technology and fuel types from EPA (2011). 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 (2011) and EIA (2011a) datasets. The difference in wood biomass consumption 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 (2011a).

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 – TO BE UPDATED

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

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[87] 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.

[88] 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.

Tier 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.[89] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[90] However, the CH_4 emission factors differ from those used by EIA. Since these factors were obtained from IPCC/UNEP/OECD/IEA (1997), uncertainty ranges were assigned based on IPCC default uncertainty estimates (IPCC 2000).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-17. Stationary combustion CH_4 emissions in 2009 (including biomass) were estimated to be between 4.1 and 14.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 34 percent below to 127 percent above the 2009 emission estimate of 6.2 Tg CO_2 Eq.[91] Stationary combustion N_2O emissions in 2009 (*including* biomass) were estimated to be between 9.8 and 36.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 23 percent below to 187 percent above the 2009 emissions estimate of 12.8 Tg CO_2 Eq.

Table 3-17: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Energy-Related Stationary Combustion, Including Biomass (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2009 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a]**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Stationary Combustion	CH_4	6.2	4.1	14.0	-34%	+127%
Stationary Combustion	N_2O	12.8	9.8	36.7	-23%	+187%

[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 2009. Details on the emission trends through time are described in more detail in the Methodology section, above.

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[89] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former distribution to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[90] 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.

[91] 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.

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

Historical CH_4 and N_2O emissions from stationary sources (excluding CO_2) were revised due to a few of changes, impacting the entire time series, relative to the previous Inventory. Slight changes to emission estimates for sectors are due to revised data from EIA (2011). Wood consumption data in EIA (2011) were revised for the residential, commercial, electric power, and industrial sectors from 1990 to 2009. Additionally, a Tier 2 emission estimation methodology was applied to estimate emissions from the electric power sector across the entire time series. This primarily impacted N_2O emission estimates, as the number of coal fluidized bed boilers increased significantly from 2000 through 2005. The combination of the methodological and historical data changes resulted in an average annual increase of 0.04 Tg CO_2 Eq. (0.5 percent) in CH_4 emissions from stationary combustion and an average annual increase of 2.0 Tg CO_2 Eq. (13.8 percent) in N_2O emissions from stationary combustion for the period 1990 through 2009.

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.

Beginning in 2010, those facilities that emit over 25,000 tons of greenhouse gases (CO_2 Eq.) from stationary combustion across all sectors of the economy are required to calculate and report their greenhouse gas emissions to EPA through its GHGRP. These data will be used in future inventories to improve the emission calculations through the use of these collected higher tier methodological data.

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. [92]

CH_4 and N_2O from Mobile Combustion – TO BE UPDATED

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.

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

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)[93] are based on VMT and emission factors by vehicle and fuel type.

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 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.[94]

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 2010 were obtained from the Federal Highway Administration’s (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2010).[95] 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 2010) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2010). VMT for AFVs were taken from Browning (2003). The age distributions of the U.S. vehicle fleet were obtained from EPA (2010a, 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 (1993, 1994a, 1994b, 1998, 1999a) and IPCC/UNEP/OECD/IEA (1997).

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).[96] Activity

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[93] 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.

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

[95] Fuel use by vehicle class (VM-1 table) was not available from FHWA for 2009, but changes in overall diesel and gasoline consumption were released in Table MF21. Fuel use in vehicle classes that were predominantly gasoline were estimated to grow by the rate of growth for gasoline between 2008 and 2009. Fuel use in vehicle classes that were predominantly diesel were estimated to fall by the same rate that diesel fuel consumption fell overall in 2009. VMT was then distributed to vehicle classes based on these fuel consumption estimates, assuming no relative change in MPG between vehicle classes.

[96] The consumption of international bunker fuels is not included in these activity data, but is estimated separately under the

data were obtained from AAR (2009 through 2010), APTA (2007 through 2010), APTA (2006), BEA (1991 through 2005), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2008), DOE (1993 through 2010), DESC (2011), DOT (1991 through 2010), EIA (2008a, 2007a, 2007b, 2002), EIA (2007 through 2010), EIA (1991 through 2011), EPA (2009), Esser (2003 through 2004), FAA (2011, 2010, and 2006), Gaffney (2007), and (2006 through 2010). Emission factors for non-road modes were taken from IPCC/UNEP/OECD/IEA (1997) and Browning (2009).

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted for the mobile source sector using the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, using @RISK software. The uncertainty analysis was performed on 2009 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) vehicle miles traveled (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. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors, because emissions of these gases are not regulated in the United States (and, therefore, there are not adequate 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 2009 were estimated to be between 1.8 and 2.2 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 9 percent below to 15 percent above the corresponding 2009 emission estimate of 2.0 Tg CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions from mobile sources in 2009 were estimated to be between 20.5 and 27.9 Tg CO_2 Eq., indicating a range of 14 percent below to 17 percent above the corresponding 2009 emission estimate of 23.9 Tg CO_2 Eq.

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

Source	**Gas**	**2009 Emission Estimate[a]**	**Uncertainty Range Relative to Emission Estimate[a]**			
		(Tg CO_2 Eq.)	**(Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Mobile Sources	CH_4	2.0	1.8	2.2	-9%	+15%
Mobile Sources	N_2O	23.9	20.5	27.9	-14%	+17%

[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 Tier 2 approach to 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 2008. 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

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International Bunker Fuels source category.

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

In order to ensure that these estimates are continuously improved, the calculation methodology is revised annually based on comments from internal and external reviewers. Each year, a number of adjustments are made to the methodologies used in calculating emissions in the current Inventory relative to previous inventory reports. One of the revisions that were made this year was incorporating motor vehicle age distribution from EPA's MOtor Vehicle Emission Simulator (MOVES) model. MOVES is EPA's tool for estimating emissions from highway vehicles, based on analysis of millions of emission test results and considerable advances in EPA's understanding of vehicle emissions. Population data from the MOVES model was used to estimate the age distribution of motor vehicles in the United States.

Planned Improvements

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

1. Develop updated emissions factors for diesel vehicles, motorcycle, and biodiesel vehicles. Previous emission factors were based upon extrapolations from other vehicle classes and new test data from Environment Canada and other sources may allow for better estimation of emission factors for these vehicles.
2. Develop new emission factors for non-road equipment. The current inventory estimates for non-CO_2 emissions from non-road sources are based on emission factors from IPCC guidelines published in 1996. Recent data on non-road sources from Environment Canada and the California Air Resources Board will be investigated in order to assess the feasibility of developing new N_2O and CH_4 emissions factors for non-road equipment.
3. Examine the feasibility of estimating aircraft N_2O and CH_4 emissions by the number of takeoffs and landings, instead of total fuel consumption. Various studies have indicated that aircraft N_2O and CH_4 emissions are more dependent on aircraft takeoffs and landings than on total aircraft fuel consumption; however, aircraft emissions are currently estimated from fuel consumption data. FAA's SAGE and AEDT databases contain detailed data on takeoffs and landings for each calendar year starting in 2000, and could potentially be used to conduct a Tier II analysis of aircraft emissions. This methodology will require a detailed analysis of the number of takeoffs and landings by aircraft type on domestic trips, the development of procedures to develop comparable estimates for years prior to 2000, and the dynamic interaction of ambient air with aircraft exhausts is developed. The feasibility of this approach will be explored.

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 will be investigated. 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. As MOVES goes through additional testing and refinement, 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 62 percent of the total C consumed for non-energy purposes was stored in products, and not released to the atmosphere; the remaining 38 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of the 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 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 make adjustments to address the effect of net exports on the mass of C in non-energy applications.

As shown in Table 3-19, fossil fuel emissions in 2010 from the non-energy uses of fossil fuels were 119.4 Tg CO_2 Eq., which constituted approximately 2 percent of overall fossil fuel emissions. In 2010, the consumption of fuels for non-energy uses (after the adjustments described above) was 4,415.2 TBtu, an increase of 0.3 percent since 1990 (see Table 3-20). About 49.9 Tg of the C (183.1 Tg CO_2 Eq.) in these fuels was stored, while the remaining 32.6 Tg C (119.4 Tg CO_2 Eq.) was emitted.

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

Year	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Potential Emissions	307.2	380.1	375.9	367.1	355.6	333.1	297.3	302.5
C Stored	191.3	237.7	236.3	229.1	225.2	198.0	179.0	183.1
Emissions as a % of Potential	38%	37%	37%	38%	37%	41%	40%	39%
Emissions	**115.8**	**142.5**	**139.6**	**138.0**	**130.4**	**135.0**	**118.2**	**119.4**

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 (2011) (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 chapter.[97] 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.

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[97] 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.

- 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 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/UNEP/OECD/IEA (1997), 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**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Industry	**4,138.4**	**5,192.2**	**5,124.0**	**4,945.4**	**4,826.0**	**4,483.0**	**4,118.8**	**4,217.7**
Industrial Coking Coal	+	53.6	80.5	62.9	2.3	29.1	6.4	64.9
Industrial Other Coal	8.2	12.4	11.9	11.9	11.9	11.9	11.9	11.9
Natural Gas to Chemical Plants	263.2	418.6	389.4	228.0	222.4	227.0	219.5	221.9
Asphalt & Road Oil	1,170.2	1,275.7	1,323.2	1,261.2	1,197.0	1,012.0	873.1	877.8
LPG	1,118.7	1,606.9	1,443.9	1,489.8	1,479.4	1,416.9	1,467.2	1,545.8
Lubricants	186.3	189.9	160.2	156.1	161.2	149.6	134.5	149.5
Pentanes Plus	77.5	229.3	146.3	105.4	132.4	114.7	93.2	103.6
Naphtha (<401 ° F)	325.8	593.7	679.6	617.5	541.4	466.7	449.7	471.3
Other Oil (>401 ° F)	661.2	533.8	499.5	572.7	667.7	598.5	391.7	403.7
Still Gas	21.3	12.6	67.7	57.2	44.2	47.3	133.9	147.2
Petroleum Coke	27.2	7.5	105.2	134.2	117.8	147.4	112.1	3.0
Special Naphtha	100.7	94.4	60.9	68.9	75.3	83.1	44.1	25.5
Distillate Fuel Oil	7.0	11.7	11.7	17.5	17.5	17.5	17.5	17.5
Waxes	33.3	33.1	31.4	26.1	21.9	19.1	12.2	15.4
Miscellaneous Products	137.8	119.2	112.8	136.0	133.5	142.0	151.8	158.8
Transportation	**176.0**	**179.4**	**151.3**	**147.4**	**152.2**	**141.3**	**127.1**	**141.2**
Lubricants	176.0	179.4	151.3	147.4	152.2	141.3	127.1	141.2
U.S. Territories	**86.7**	**152.2**	**121.9**	**133.4**	**108.4**	**126.7**	**56.3**	**56.3**
Lubricants	0.7	3.1	4.6	6.2	5.9	2.7	1.0	1.0
Other Petroleum (Misc. Prod.)	86.0	149.1	117.3	127.2	102.5	124.1	55.2	55.2
Total	**4,401.1**	**5,523.7**	**5,397.2**	**5,226.2**	**5,086.6**	**4,751.0**	**4,302.1**	**4,415.2**

+ Does not exceed 0.05 TBtu

Note: To avoid double-counting, coal coke, petroleum coke, natural gas consumption, and other oils are adjusted for industrial process consumption reported in the Industrial Processes sector. Natural gas, LPG, Pentanes Plus, Naphthas, Special Naphtha, and Other Oils are adjusted to account for exports of chemical intermediates derived from these fuels. For residual oil (not shown in the table), all non-energy use is assumed to be consumed in C black production, which is also reported in the Industrial Processes chapter.

Note: Totals may not sum due to independent rounding.

Table 3-21: 2010 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (Tg C/QBtu)	Potential Carbon (Tg C)	Storage Factor	Carbon Stored (Tg C)	Carbon Emissions (Tg C)	Carbon Emissions (Tg CO_2 Eq.)
Industry	**4,217.7**	-	**78.5**	-	**49.6**	**28.9**	**106.1**
Industrial Coking Coal	64.9	25.61	1.7	0.10	0.2	1.5	5.5
Industrial Other Coal	11.9	25.82	0.3	0.59	0.2	0.1	0.5
Natural Gas to Chemical Plants	221.9	14.47	3.2	0.59	1.9	1.3	4.8
Asphalt & Road Oil	877.8	20.55	18.0	1.00	18.0	0.1	0.3
LPG	1,545.8	17.06	26.4	0.59	15.7	10.7	39.3
Lubricants	149.5	20.20	3.0	0.09	0.3	2.7	10.1
Pentanes Plus	103.6	19.10	2.0	0.59	1.2	0.8	2.9
Naphtha (<401° F)	471.3	18.55	8.7	0.59	5.2	3.5	13.0
Other Oil (>401° F)	403.7	20.17	8.1	0.59	4.8	3.3	12.1
Still Gas	147.2	17.51	2.6	0.59	1.5	1.0	3.8
Petroleum Coke	3.0	27.85	0.1	0.30	+	0.1	0.2
Special Naphtha	25.5	19.74	0.5	0.59	0.3	0.2	0.7
Distillate Fuel Oil	17.5	20.17	0.4	0.50	0.2	0.2	0.6
Waxes	15.4	19.80	0.3	0.58	0.2	0.1	0.5
Miscellaneous Products	158.8	20.31	3.2	+	+	3.2	11.8
Transportation	**141.2**	-	**2.9**	-	**0.3**	**2.6**	**9.5**
Lubricants	141.2	20.20	2.9	0.09	0.3	2.6	9.5
U.S. Territories	**56.3**	-	**1.1**	-	**0.1**	**1.0**	**3.7**
Lubricants	1.0	20.20	+	0.09	+	+	0.1
Other Petroleum (Misc. Prod.)	55.2	20.00	1.1	0.10	0.1	1.0	3.6
Total	**4,415.2**		**82.5**		**49.9**	**32.6**	**119.4**

+ Does not exceed 0.05 Tg

- Not applicable.

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

Note: Totals may not sum due to independent rounding.

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 2010), *Toxics Release Inventory, 1998* (2000b), *Biennial Reporting System* (EPA 2004, 2009), and pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Bureau of the Census (1999, 2004, 2009); Bank of Canada (2011); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (2011); Gosselin, Smith, and Hodge (1984); the Rubber Manufacturers' Association (RMA 2009a,b); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2011); and the American Chemistry Council (ACC 2003-2010, 2011). Specific data sources are listed in full detail in Annex 2.3.

Uncertainty and Time-Series Consistency - TO BE UPDATED

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

Tier 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 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 Tier 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 2009 was estimated to be between 97.6 and 135.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 21 percent below to 10 percent above the 2009 emission estimate of 123.4 Tg 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: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Feedstocks	CO_2	79.3	63.4	96.1	-20%	21%
Asphalt	CO_2	0.3	0.1	0.6	-58%	119%
Lubricants	CO_2	17.7	14.6	20.5	-17%	16%
Waxes	CO_2	0.4	0.3	0.7	-29%	74%
Other	CO_2	25.7	10.3	27.0	-60%	5%
Total	**CO_2**	123.4	97.6	135.3	-21%	10%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
NA (Not Applicable)

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

Source	**Gas**	**2010 Storage Factor (%)**	**Uncertainty Range Relative to Emission Estimate[a] (%)**		**(%, Relative)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Feedstocks	CO_2	58%	56%	60%	-3%	4%
Asphalt	CO_2	99.6%	99.1%	99.8%	-0.5%	0.3%
Lubricants	CO_2	9%	4%	17%	-57%	91%
Waxes	CO_2	58%	49%	71%	-15%	22%
Other	CO_2	17%	16%	66%	-3%	292%

[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 2009. 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 was also 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. It was determined that much of this discrepancy was driven by a change in the methodology used to account for national non-energy consumption of fossil fuels. EPA is working with EIA to improve the accuracy of these numbers.

Recalculations Discussion

Relative to the previous Inventory, emissions from non-energy uses of fossil fuels decreased by an average of 3.6 Tg CO_2 Eq. (2.6 percent) across the entire time series. It was caused primarily by a change in petrochemical input data reported by the Energy Information Administration in its Monthly Energy Review. In particular, a decline in EIA's estimate of petroleum coke consumed for non-energy purposes across the time series explains the vast majority of the decrease. As noted above, EPA and EIA are reviewing data on non-energy consumption of fossil fuels.

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 an input/output discrepancy in the carbon mass balance contained within the NEU model. In the future, EPA will pursue three strategies to reduce or eliminate this discrepancy. First, based on the results of the QAQC and verification activities discussed above, EIA conducted a review of its methodology for calculating total consumption of petrochemical feedstocks for non-energy uses in the U.S. This resulted in improved input data that are expected to lessen the discrepancy when integrated into the NEU model. Second, EPA will improve its accounting of C in imports and exports. EPA will examine its import/export adjustment methodology to ensure that net exports of intermediaries such as ethylene and propylene are fully accounted for. Third, EPA will reconsider its use of top-down C input calculation in estimating emissions. It will consider alternative approaches that rely more substantially on the bottom-up C output calculation instead.
- Improving the uncertainty analysis. Most of the input parameter distributions are based on professional judgment rather than rigorous statistical characterizations of uncertainty.
- Better characterizing flows of fossil 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). EPA plans to better understand these trends to identify any mischaracterized or misreported fuel consumption for non-energy uses.
- EPA recently researched updating the average carbon content of solvents, 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 carbon in solvents. EPA plans to identify additional sources of solvents data in order to update the C content assumptions.

Finally, 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 and 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 conducting analyses of C fate similar to those described in Annex 2.3 or deferring to more updated default storage factors from IPCC where available.

Finally improvements to this category will involve analysis of the data reported under EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the carbon emitted from non-energy uses of fossil fuels 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. [98]

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.

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

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 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 carbon mass balance for non-energy uses of fossil fuels.

Approximately 26.5 million metric tons of MSW was incinerated in the United States in 2010 (EPA 2011a). CO_2 emissions from incineration of waste rose 51 percent since 1990, to an estimated 12.1 Tg CO_2 Eq. (12,054 Gg) in 2010, 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 N_2O and CH_4 emissions (De Soete 1993; IPCC 2006). N_2O emissions from the incineration of waste were estimated to be 0.4 Tg CO_2 Eq. (1 Gg N_2O) in 2010, and have not changed significantly since 1990. CH_4 emissions from the incineration of waste were estimated to be less than 0.05 Tg CO_2 Eq. (less than 0.5 Gg CH_4) in 2010, and have not changed significantly since 1990.

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

Gas/Waste Product	1990	2000	2005	2006	2007	2008	2009	2010
CO_2	**8.0**	**11.1**	**12.5**	**12.5**	**12.7**	**11.9**	**11.7**	**12.1**
Plastics	5.6	6.1	6.9	6.7	6.7	6.1	6.2	6.6
Synthetic Rubber in Tires	0.3	1.5	1.6	1.7	1.8	1.7	1.6	1.6
Carbon Black in Tires	0.4	1.8	2.0	2.1	2.3	2.1	1.9	1.9
Synthetic Rubber in MSW	0.9	0.7	0.8	0.8	0.8	0.8	0.8	0.8
Synthetic Fibers	0.8	1.1	1.2	1.2	1.2	1.2	1.2	1.2
N_2O	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
CH_4	+	+	+	+	+	+	+	+
Total	**8.5**	**11.5**	**12.9**	**12.9**	**13.1**	**12.3**	**12.1**	**12.4**

+ Does not exceed 0.05 Tg CO_2 Eq.

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

Gas/Waste Product	1990	2000	2005	2006	2007	2008	2009	2010
CO_2	**7,989**	**11,117**	**12,468**	**12,531**	**12,727**	**11,888**	**11,703**	**12,054**
Plastics	5,588	6,104	6,919	6,722	6,660	6,148	6,233	6,573
Synthetic Rubber in Tires	308	1,454	1,599	1,712	1,823	1,693	1,560	1,560
Carbon Black in Tires	385	1,818	1,958	2,113	2,268	2,085	1,903	1,903
Synthetic Rubber in MSW	872	689	781	775	791	770	782	787
Synthetic Fibers	838	1,051	1,211	1,208	1,185	1,192	1,226	1,230
N_2O	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
CH_4	+	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg.

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 3.6.

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 2011b) and detailed unpublished backup data for some years not shown in the reports (Schneider 2007). 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 2010 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 2005-2009 data (RMA 2011). For 2010, synthetic rubber mass in tires is assumed to be equal to that in 2009 due to a lack of more recently available data.

Average C contents for the "Other" plastics category and synthetic rubber in municipal solid wastes were calculated from 1998 and 2002 production statistics: carbon content for 1990 through 1998 is based on the 1998 value; content for 1999 through 2001 is the average of 1998 and 2002 values; and 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 on total waste incinerated was not available for 2009 or 2010, so this value was assumed to equal the most recent value available (2008).

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 for National Greenhouse Gas Inventories (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
2000	252,328,354	25,974,978	10.3
2005	259,559,787	25,973,520	10.0
2006	267,526,493	25,853,401	9.7
2007	268,279,240	24,788,539	9.2
2008	268,541,088	23,674,017	8.8
2009	268,541,088[a]	23,674,017 [a]	8.8[a]
2010	268,541,088[a]	23,674,017 [a]	8.8[a]

[a] Assumed equal to 2008 value.
Source: van Haaren et al. (2010).

Uncertainty and Time-Series Consistency

A Tier 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 Tier 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 Tier 2 quantitative uncertainty analysis are summarized in Table 3-27. Waste incineration CO_2 emissions in 2010 were estimated to be between 9.6and 14.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 21 percent below to 24 percent above the 2010 emission estimate of 12.1 Tg CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2010 were estimated to be between 0.2 and 1.5 Tg CO_2 Eq. This indicates a range of 50 percent below to 320 percent above the 2010 emission estimate of 0.4 Tg CO_2 Eq.

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

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]	
			(Tg CO_2 Eq.)	(%)

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	12.1	9.6	14.9	-21%	+24%
Incineration of Waste	N_2O	0.4	0.2	1.5	-50%	+320%

[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 2010. 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

Several changes were made to input variables compared to the previous Inventory, resulting in an overall decrease in the total emissions from the incineration of waste. The emissions from carbon black and rubber in scrap tires in 2008 and 2009 were updated based on data obtained from the Rubber Manufacturers' Association U.S. Scrap Tire Management Summary for 2005-2009 (RMA 2012b), because the report releases data every other year. The 2009 data was available in this report, so 2008 data was updated using linear interpolation from the 2007 and 2009 data. The change decreased the 2008 and 2009 emissions by 2 percent and 5 percent, respectively, relative to the previous report.

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 U.S. 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[99], 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 chapter of this report. In examining data from EPA's Greenhouse Gas Reporting Program 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 Greenhouse Gas Reporting Program are not available for all inventory years as reported in this inventory. Additionally, analyses will focus on ensuring CO2 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. GHG emissions. In implementing improvements and integration of data from EPA's Greenhouse Gas Reporting Program, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[100]

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

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

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. Underground coal mines contribute the largest share of CH_4 emissions. In 2010, 164 gassy underground coal mines in the United States employ ventilation systems to ensure that CH_4 levels remain within safe concentrations. These systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Additionally, 24 U.S. coal mines supplement ventilation systems with degasification systems. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large volumes of CH_4 before, during, or after mining. In 2010, 15 coal mines collected CH_4 from degasification systems and utilized this gas, thus reducing emissions to the atmosphere. Of these mines, 14 coal mines sold CH_4 to the natural gas pipeline and one coal mine used CH_4 from its degasification system to heat mine ventilation air on site. In addition, one of the coal mines that sold gas to pipelines also used CH_4 to fuel a thermal coal dryer. Surface coal mines also release CH_4 as the overburden is removed and the coal is exposed, but the level of emissions is much lower than from underground mines. Finally, some of the CH_4 retained in the coal after mining is released during processing, storage, and transport of the coal.

Total CH_4 emissions in 2010 were estimated to be 72.6 Tg CO_2 Eq. (3,458 Gg), a decline of 14 percent since 1990 (see Table 3-28 and Table 3-29). Of this amount, underground mines accounted for 71 percent, surface mines accounted for 18 percent, and post-mining emissions accounted for 11 percent. The decline in CH_4 emissions from underground mines from 1996 to 2002 was the result of the reduction of overall coal production, the mining of less gassy coal, and an increase in CH_4 recovered and used. Since that time, underground coal production and the associated CH_4 emissions have remained fairly level, while surface coal production and its associated emissions have generally increased.

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

Activity	1990	2005	2006	2007	2008	2009	2010
UG Mining	62.3	34.9	34.9	35.7	44.9	49.6	51.6
Liberated	67.9	50.2	50.2	50.9	60.5	66.1	71.4
Recovered & Used	(5.6)	(15.2)	(18.8)	(15.2)	(16.3)	(16.6)	(19.6)
Surface Mining	12.0	13.3	14.0	13.8	14.3	12.9	13.1
Post-Mining (UG)	7.7	6.4	6.3	6.1	6.1	5.6	5.7
Post-Mining (Surface)	2.0	2.2	2.3	2.2	2.3	2.1	2.1
Total	**84.1**	**56.8**	**56.8**	**57.8**	**66.9**	**70.1**	**72.6**

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

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

Activity	1990	2005	2006	2007	2008	2009	2010
UG Mining	2,968	1,663	1,693	1,698	2,102	2,360	2,459
Liberated	3,234	2,389	2,588	2,422	2,881	3,149	3,402
Recovered & Used	(266)	(726)	(895)	(724)	(779)	(789)	(943)
Surface Mining	573.6	633.1	668.0	658.9	680.5	614.2	626.2
Post-Mining (UG)	368.3	305.9	298.5	289.6	292.0	266.7	270.2
Post-Mining (Surface)	93.2	102.9	108.5	107.1	110.6	99.8	101.8
Total	**4,003**	**2,705**	**2,768**	**2,754**	**3,186**	**3,340**	**3,458**

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 parts. The first part involves estimating CH_4 emissions from underground mines. Because of the availability of ventilation system measurements, underground mine emissions can be estimated on a mine-by-mine basis and then summed to determine total emissions. The second step involves estimating emissions from surface mines and post-mining activities by multiplying basin-specific coal production by basin-specific emission factors.

Underground mines. Total CH_4 emitted from underground mines was estimated as the sum of CH_4 liberated from ventilation systems and CH_4 liberated by means of degasification systems, minus CH_4 recovered and used. The

Mine Safety and Heath Administration (MSHA) samples CH_4 emissions from ventilation systems for all mines with detectable[101] CH_4 concentrations. These mine-by-mine measurements are used to estimate CH_4 emissions from ventilation systems.

Some of the higher-emitting underground mines also use degasification systems (e.g., wells or boreholes) that remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Various approaches were employed to estimate the quantity of CH_4 collected by each of the twenty mines using these systems, depending on available data. For example, some mines report to EPA the amount of CH_4 liberated from their degasification systems. For mines that sell recovered CH_4 to a pipeline, pipeline sales data published by state petroleum and natural gas agencies were used to estimate degasification emissions. For those mines for which no other data are available, default recovery efficiency values were developed, depending on the type of degasification system employed.

Finally, the amount of CH_4 recovered by degasification systems and then used (i.e., not vented) was estimated. In 2010, 14 active coal mines sold recovered CH_4 into the local gas pipeline networks and one coal mine used recovered CH_4 on site for heating. Emissions avoided for these projects were estimated using gas sales data reported by various state agencies. For most mines with recovery systems, companies and state agencies provided individual well production information, which was used to assign gas sales to a particular year. For the few remaining mines, coal mine operators supplied information regarding the number of years in advance of mining that gas recovery occurs.

Surface Mines and Post-Mining Emissions. Surface mining and post-mining CH_4 emissions were estimated by multiplying basin-specific coal production, obtained from the Energy Information Administration's Annual Coal Report (see Table 3-30) (EIA 2011), by basin-specific emission factors. Surface mining emission factors were developed by assuming that surface mines emit two times as much CH_4 as the average in situ CH_4 content of the coal. Revised data on in situ CH_4 content and emissions factors are taken from EPA (2005), EPA (1996), and AAPG (1984). This calculation accounts for CH_4 released from the strata surrounding the coal seam. For post-mining emissions, the emission factor was assumed to be 32.5 percent of the average in situ CH_4 content of coals mined in the basin.

Table 3-30: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total
1990	384,244	546,808	931,052
2005	334,398	691,448	1,025,846
2006	325,697	728,447	1,054,144
2007	319,139	720,023	1,039,162
2008	323,932	737,832	1,061,764
2009	301,241	671,475	972,716
2010	305,862	693,732	999,594

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Tier 2 uncertainty estimation methodology. Because emission estimates from underground ventilation systems were based on actual measurement data, 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 and Wang 2000). Estimates of CH_4 recovered by degasification systems are relatively certain because many coal mine operators provided information on individual well gas sales and mined through dates. Many of the recovery estimates use data on wells within 100 feet of a mined area. Uncertainty also exists concerning the radius of influence of each well. The number of wells counted,

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[101] 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.

and thus the avoided emissions, may vary if the drainage area is found to be larger or smaller than currently estimated.

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 Tier 2 quantitative uncertainty analysis are summarized in Table 3-31. Coal mining CH_4 emissions in 2010 were estimated to be between 63.0 and 84.4 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 13.2 percent below to 16.3 percent above the 2010 emission estimate of 72.6 Tg CO_2 Eq.

Table 3-31: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Coal Mining (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Coal Mining	CH_4	72.6	63.0	84.4	-13.2%	+16.3%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, updated mine maps were received for the Oak Grove and Jim Walter Resources (JWR) mines, which provided a more accurate depiction of the dates that certain pre-drainage CMM wells were mined through. As a result, the mined-through dates were adjusted for some wells based on updated mine plans, and underground emissions avoided values changed slightly from 2005 to 2009.

Data was not available for CDX wells for 2010, thus underground emissions avoided were estimated for two mines. Emissions avoided were estimated using a 10-year average for the Pinnacle Mine and a 2-year average for the Road Fork 51 Mine.

Planned Improvements

Beginning in 2011, those underground coal mines that are subject to quarterly or more frequent sampling by Mine Safety and Health Administration (MSHA) of ventilation systems are required to calculate and report their greenhouse gas emissions to EPA through its Greenhouse Gas Reporting Program. These data will be examined for its use in future inventories to improve the emission calculations consistent with the latest guidance from the IPCC on the use of facility-level data in national inventories.[102]

3.5. Abandoned Underground Coal Mines (IPCC Source Category 1B1a)

Underground coal mines contribute the largest share of CH_4 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, the 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

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

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.

Gross abandoned mine CH_4 emissions ranged from 6.0 to 9.1 Tg CO_2 Eq. from 1990 through 2010, varying, in general, by less than 1 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 (9.1 Tg CO_2 Eq.) due to the large number of mine closures from 1994 to 1996 (70 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. There were fewer than fifteen gassy mine closures during each of the years from 1998 through 2010, with only five closures in 2010. By 2010, gross abandoned mine emissions decreased slightly to 7.6 Tg CO_2 Eq. (see Table 3-32 and Table 3-33). Gross emissions are reduced by CH_4 recovered and used at 38 mines, resulting in net emissions in 2010 of 5.0 Tg CO_2 Eq.

Table 3-32: CH_4 Emissions from Abandoned Coal Mines (Tg CO_2 Eq.)

Activity	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Abandoned Underground Mines	6.0	8.9	8.9	7.0	7.6	8.9	9.0	8.1	7.6
Recovered & Used	+	0.7	1.5	1.5	2.2	3.6	3.7	3.0	2.7
Total	**6.0**	**8.2**	**7.4**	**5.5**	**5.5**	**5.3**	**5.3**	**5.1**	**5.0**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 3-33: CH_4 Emissions from Abandoned Coal Mines (Gg)

Activity	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Abandoned Underground Mines	288	424	422	334	364	425	429	388	364
Recovered & Used	+	32	72	70	103	172	177	143	126
Total	**288**	**392**	**350**	**264**	**261**	**254**	**253**	**244**	**237**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

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 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. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure, for a vented mine, and the PI term is essentially constant at the pressures of interest (atmospheric to 30 psia). 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:

$$q = q_i (1+bD_it)^{(-1/b)}$$

where,

q = Gas rate at time t in mmcf/d
q_i = Initial gas rate at time zero (t_o) in million cubic feet per day 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 2003).

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 flooding 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 2003).

$$q = q_{ie}^{(-Dt)}$$

where,

q = Gas flow rate at time t in mcf/d
q_i = Initial gas flow rate at time zero (t_o) in mcfd
D = Decline rate, 1/yr
t = Elapsed time from t_o (years)

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the rate that would be emitted if the mine had an open vent. The total volume emitted will be the same, but will occur over a longer period. The methodology, therefore, treats the emissions prediction from a sealed mine similar to emissions from a vented mine, but uses a lower initial rate depending on the degree of sealing. The computational fluid dynamics simulator was again 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 2003).

For active coal mines, those mines producing over 100 mcfd account for 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that 469 abandoned mines closing after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 273 of the 469 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 were placed in one of the three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2003).

Table 3-34: Number of gassy abandoned mines occurring in U.S. basins grouped by class according to post-abandonment state

Basin	**Sealed**	**Vented**	**Flooded**	**Total Known**	**Unknown**	**Total Mines**
Central Appl.	25	25	48	98	129	227
Illinois	30	3	14	47	26	73
Northern Appl.	42	22	16	80	36	116
Warrior Basin	0	0	16	16	0	16
Western Basins	27	3	2	32	10	42
Total	**124**	**53**	**96**	**273**	**196**	**474**

Inputs to the decline equation require the average emission rate and the date of abandonment. Generally this data is available for mines abandoned after 1972; however, such data are largely unknown for mines closed before 1972. Information that is readily available such as coal production by state and county are helpful, but do not provide enough data to directly employ the methodology used to calculate emissions from mines abandoned after 1971. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1972 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 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 2003).

Abandoned mines 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 ventilated for the total CH_4 liberation rate for seventeen mines that closed between 1992 and 2010. Since the sample of gassy mines (with active mine emissions greater than 100 mcfd) is assumed to account for 78 percent of the pre-1971 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 2010, 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 in 1990 through 1992, because no data was reported for abandoned coal mining CH_4 recovery projects during that time.

Uncertainty

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 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 Tier 2 quantitative uncertainty analysis are summarized in Table 3-35. Abandoned coal mines CH_4 emissions in 2010 were estimated to be between 3.88 and 6.05 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 22 percent below to 21 percent above the 2010 emission estimate of 4.98 Tg CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is used in the methodology. The largest degree of uncertainty is associated with the unknown status mines (which account for 42 percent of the mines), with a ±51 percent uncertainty.

Table 3-35: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	4.98	3.88	6.05	-22%	+21%

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

3.6. 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 215.0 Tg CO_2 Eq. (10,238 Gg) of CH_4 in 2010, a 13 percent increase over 1990 emissions (see Table 3-36 and Table 3-37), and 32.3 Tg CO_2 Eq. (32,297 Gg) of non-combustion CO_2 in 2010, a 14 percent decrease over 1990 emissions (see Table 3-38 and Table 3-40). Improvements in management practices and technology, along with the replacement of older equipment, have helped to stabilize emissions. Methane emissions increased since 2008 due to an increase in production and production wells.

CH_4 and non-combustion CO_2 emissions from natural gas systems are generally process related, with normal operations, routine maintenance, and system upsets being the primary contributors. Emissions from normal operations include: natural gas engines and turbine uncombusted exhaust, bleed and discharge emissions from pneumatic devices, 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 devices, well clean-ups, and gas well completions and re-completions (workovers) with and without hydraulic fracturing account for the majority of CH_4 emissions. Flaring emissions account for the majority of the non-combustion CO_2 emissions. Emissions from field production accounted for approximately 58 percent of CH_4 emissions and about 34 percent of non-combustion CO_2 emissions from natural gas systems in 2010.

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 about 8 percent of CH_4 emissions and approximately 66 percent of non-combustion CO_2 emissions from natural gas systems.

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 United States transmission system. Fugitive CH_4 emissions from these compressor stations and from metering and regulating stations account for the majority of the emissions from this stage. Pneumatic devices and engine uncombusted exhaust 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 20 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.

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 over 1,202,000 miles of distribution mains in 2010, an increase from just over 258,000 miles in 1990 (OPS 2010b). Distribution system emissions, which account for approximately 13 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 gate stations and pipelines. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced emissions from this stage. Distribution system CH_4 emissions in 2010 were 15 percent lower than 1990 levels.

Table 3-36: CH_4 Emissions from Natural Gas Systems (Tg CO_2 Eq.)*

Stage	**1990**	**2000**	**2006**	**2007**	**2008**	**2009**	**2010**
Field Production	89.0	113.2	115.5	118.1	118.6	128.9	125.6
Processing	18.0	17.8	14.8	15.5	16.2	17.8	17.1
Transmission and Storage	49.2	46.7	40.9	42.5	43.3	44.7	43.8
Distribution	33.4	31.4	28.3	29.4	29.9	29.1	28.5
Total	**189.6**	**209.2**	**199.5**	**205.5**	**208.0**	**220.5**	**215.0**

*These values represent CH4 emitted to the atmosphere. CH_4 that is captured (and not emitted to the atmosphere) is calculated and removed from emission totals.

Note: Totals may not sum due to independent rounding.

Table 3-37: CH_4 Emissions from Natural Gas Systems (Gg)*

Stage	**1990**	**2000**	**2006**	**2007**	**2008**	**2009**	**2010**
Field Production	4,239	5,392	5,624	5,624	5,646	6,140	5,980
Processing	855	848	704	737	770	837	812
Transmission and Storage	2,343	2,223	1,949	2,024	2,062	2,127	2,086
Distribution	1,591	1,497	1,346	1,402	1,426	1,384	1,359
Total	**9,029**	**9,960**	**9,499**	**9,787**	**9,904**	**10,498**	**10,238**

* These values represent CH4 emitted to the atmosphere. CH_4 that is captured (and not emitted to the atmosphere) is calculated and removed from emission totals.

Note: Totals may not sum due to independent rounding.

Table 3-38: CH_4 Calculated Potential CH_4 and Captured/Combusted CH_4 from Natural Gas Systems (Tg CO_2 Eq.)

Calculated Potential	**1990**	**2000**	**2006**	**2007**	**2008**	**2009**	**2010**
Field Production	88.9	126.2	161.1	174.4	181.5	185.6	184.6
Processing	17.9	18.4	17.7	18.3	19.0	19.3	20.1
Transmission and Storage	49.2	52.1	51.0	52.0	52.6	52.5	53.0
Distribution	33.4	32.0	29.3	30.2	30.5	29.9	29.6
Total Potential	***189.4***	***228.6***	***259.0***	***274.8***	***283.5***	***287.3***	***287.3***
Captured/Combusted	**1990**	**2000**	**2006**	**2007**	**2008**	**2009**	**2010**
Field Production	+	13.0	45.5	56.3	62.9	56.7	59.1
Processing	+	0.6	2.9	2.8	2.8	1.5	3.0
Transmission and Storage	+	5.4	10.1	9.5	9.2	7.8	9.2
Distribution	+	0.6	1.0	0.8	0.6	0.9	1.1

Total Captured/Combusted	***-0.2****	***19.6***	***59.5***	***69.3***	***75.5***	***66.8***	***72.3***
Net Emissions	**1990**	**2000**	**2006**	**2007**	**2008**	**2009**	**2010**
Field Production	89.0	113.2	115.5	118.1	118.6	128.9	125.6
Processing	18.0	17.8	14.8	15.5	16.2	17.8	17.1
Transmission and Storage	49.2	46.7	40.9	42.5	43.3	44.7	43.8
Distribution	33.4	31.4	28.3	29.4	29.9	29.1	28.5
Total Emissions	***189.6***	***209.2***	***199.5***	***205.5***	***208.0***	***220.5***	***215.0***

Note: Totals may not sum due to independent rounding.

*The base year of the factors used is 1992; for reductions reported between 1990 and 1992, it is assumed that reductions are already taken into account in the Calculated Potential values and the reduction is added back into the estimate for the appropriate year(s). For 1990, this table shows the value added back into the estimate.

+ Emissions are less than 0.1 Tg CO_2 Eq.

Table 3-39: Non-combustion CO_2 Emissions from Natural Gas Systems (Tg CO_2 Eq.)

Stage	**1990**	**2000**	**2006**	**2007**	**2008**	**2009**	**2010**
Field Production	9.7	6.4	8.8	9.7	11.3	10.9	10.8
Processing	27.8	23.3	21.2	21.2	21.4	21.2	21.3
Transmission and Storage	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Distribution	+	+	+	+	+	+	+
Total	**37.6**	**29.9**	**30.1**	**31.0**	**32.8**	**32.2**	**32.3**

Note: Totals may not sum due to independent rounding.

+ Emissions are less than 0.1 Tg CO_2 Eq.

Table 3-40: Non-combustion CO_2 Emissions from Natural Gas Systems (Gg)

Stage	**1990**	**2000**	**2006**	**2007**	**2008**	**2009**	**2010**
Field Production	9,703	6,424	8,801	9,743	11,319	10,871	10,844
Processing	27,763	23,343	21,214	21,199	21,385	21,188	21,346
Transmission and Storage	62	64	63	64	65	65	65
Distribution	46	44	40	41	42	41	41
Total	**37,574**	**29,876**	**30,755**	**31,050**	**32,828**	**32,171**	**32,171**

Note: Totals may not sum due to independent rounding.

Methodology

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 same factors were used to estimate both CH_4 and non-combustion CO_2 emissions. CO2 factors were developed using the CH_4 emission factors and average CO2 and CH4 content of gas. The EPA/GRI study was based on a combination of process engineering studies and measurements at representative gas facilities. From this analysis, a 1992 emission estimate was developed using the emission factors and activity data drivers from the study, except where direct activity data was available (e.g., offshore platform counts, processing plant counts, transmission pipeline miles, and distribution pipelines). For other years, a set of industry activity data drivers was developed that can be used to update activity data, where such data is not directly available. These 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.

Although the inventory primarily uses EPA/GRI emission factors, significant improvements were made to the emissions estimates for three sources with last year's inventory: gas well cleanups, condensate storage tanks and centrifugal compressors. In addition, data for two sources not included in the EPA/GRI study – gas well completions and gas well workovers (re-completions) with hydraulic fracturing- were added. In the case of gas well cleanups, the methodology was revised to use a large sample of well and reservoir characteristics from the HPDI database (HPDI 2009) along with an engineering statics equation (EPA 2006a) to estimate the volume of natural gas necessary to expel a liquid column choking the well production. See Annex 3.4 for more information on the methodology for gas well clean ups. For condensate storage tanks, sample E&P Tank runs were used as was the case in previous inventories; however, the factor was improved by using a large sample distribution of condensate production by gravity from the HPDI database (HPDI 2009) to weigh the sample simulation flashing emissions rather than assuming a uniform distribution of condensate gravities. Additionally, TERC (TERC 2009) data representing two regions was used in the emission factors for those two regions to estimate the effects of separator dump valves malfunctioning and allowing natural gas to vent through the downstream condensate storage tanks. The EPA/GRI emission factor for centrifugal compressors (used in earlier inventories) was derived from sampled emissions at the seal face of wet seal compressors. A World Gas Conference publication (WGC 2009) on the seal oil degassing vents was used to update this factor and to also account for the emergence of dry seal centrifugal compressors (EPA 2006b), which eliminates seal oil degassing vents and reduces overall emissions. For more information on this factor, see Annex 3.4. Previous Inventories did not differentiate between wells without hydraulic fracturing and with hydraulic fracturing for completions and workovers. Gas well completions and workovers with hydraulic fracturing were not common at the time the EPA/GRI survey was conducted. Since then, these activities have become more prevalent and emissions data on this activity has become available through a number of sources. Using this data, an emission factor was developed for gas well completions and workovers with hydraulic fracturing. See Annex 3.4 for more detailed information on the methodology and data used to calculate CH_4 and non-combustion CO_2 emissions from natural gas systems.

The emissions factors described above represent expected emissions from an activity, and do not take into account use of technologies that reduce emissions. To take into account use of such technologies, data is collected on regulatory and voluntary reductions. For more information on these reductions, please see the Annex. The numbers presented in tables 3-36 and 3-37 are the CH4 that is emitted to the atmosphere (i.e., net emissions), not potential emissions without capture or flaring.

Activity data were taken from the following sources: American Gas Association (AGA 1991–1998); Bureau of Ocean Energy Management, Regulation and Enforcement (previous Minerals and Management Service) (BOEMRE 2010a-d); Monthly Energy Review (EIA 2010f); Natural Gas Liquids Reserves Report (EIA 2005); Natural Gas Monthly (EIA 2010b,c,e); the Natural Gas STAR Program annual emissions savings (EPA 2010); Oil and Gas Journal (OGJ 1997–2010); Office of Pipeline Safety (OPS 2010a-b); Federal Energy Regulatory Commission (FERC 2010) and other Energy Information Administration publications (EIA 2001, 2004, 2010a,d); World Oil Magazine (2010a-b). 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 2009) and the Alabama State Oil and Gas Board (Alabama 2010). Other state well data was taken from: American Association of Petroleum Geologists (AAPG 2004); Brookhaven College (Brookhaven 2004); Kansas Geological Survey (Kansas 2010); Montana Board of Oil and Gas Conservation (Montana 2010); Oklahoma Geological Survey (Oklahoma 2010); Morgan Stanley (Morgan Stanley 2005); Rocky Mountain Production Report (Lippman 2003); New Mexico Oil Conservation Division (New Mexico 2010, 2005); Texas Railroad Commission (Texas 2010a-d); Utah Division of Oil, Gas and Mining (Utah 2010). Emission factors were taken from EPA/GRI (1996). GTI's Unconventional Natural Gas and Gas Composition Databases (GTI 2001) were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors and adjust CH_4 emission factors from the EPA/GRI survey. Methane compositions from GTI 2001 are adjusted year to year using gross production by NEMS for oil and gas supply regions from the EIA. Therefore, emission factors may vary from year to year due to slight changes in the methane composition for each NEMS oil and gas supply module region. 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.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted to determine the level of uncertainty surrounding estimates of emissions from natural gas systems. Performed using @RISK software and the IPCC-recommended Tier 2 methodology (Monte Carlo Simulation technique), this 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 @RISK model utilizes 1992 (base year) emissions to quantify the uncertainty associated with the emissions estimates using the top twelve emission sources for the year 2010.

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 2010. The heterogeneous nature of the natural gas industry makes it difficult to sample facilities that are completely representative of the entire industry. Because of this, scaling up from model facilities introduces a degree of uncertainty. Additionally, highly variable emission rates were measured among many system components, making the calculated average emission rates uncertain. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-41. Natural gas systems CH_4 emissions in 2010 were estimated to be between 174.2 and 279.5 Tg CO_2 Eq. at a 95 percent confidence level. Natural gas systems non-energy CO_2 emissions in 2010 were estimated to be between 26.2 and 42.0 Tg CO_2 Eq. at 95 percent confidence level.

Table 3-41: Tier 2 Quantitative Uncertainty Estimates for CH_4 and Non-energy CO_2 Emissions from Natural Gas Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)[c]	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound[c]	**Upper Bound[c]**	**Lower Bound[c]**	**Upper Bound[c]**
Natural Gas Systems	CH_4	215.0	174.2	279.5	-19%	+30%
Natural Gas Systems[b]	CO_2	32.3	26.2	42.0	-19%	+30%

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

[b] 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.

[c] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

QA/QC and Verification Discussion

The natural gas inventory is continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practice. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. In addition, through regulations, public webcasts, and the Natural Gas STAR Program, EPA performs a QAQC check to determine the assumptions in the Inventory are consistent with current industry practices. Finally, QAQC checks are consistently conducted to minimize human error in the model calculations.

Recalculations Discussion

EPA has received information and data related to the emissions estimates through the inventory preparation process and the formal public notice and comment process of the proposed oil and gas new source performance standards (NSPS) for VOCs. EPA plans to carefully evaluate this and all other relevant information provided to us. Subsequently, all relevant updates will then be incorporated, as applicable, in the next cycle of the Inventory. See Planned Improvements below. In light of this current review of information and data, for the 1990-2010 Inventory, emissions for the natural gas sector were calculated using the same methodologies, emission factors, and sources of activity data, as the 1990-2009 Inventory. Additionally, EPA has held the 2010 estimate for emissions from hydraulically fractured wells constant at 2009 levels (i.e., maintained the same activity data and voluntary reductions for hydraulically fractured gas well completions and existing hydraulically fractured gas wells).

Some of the calculated emissions for the 1990-2009 times series have changed from last year's report due to corrections noted above in QA/QC and Verification Discussion.

Planned Improvements

EPA is considering a number of potential improvements for the Natural Gas Systems inventory.

For the production sector, EPA intends to evaluate additional data on emissions reductions, particularly those related to gas well cleanups and regulatory reductions from well completions and if appropriate, will incorporate revisions into future inventories. Additionally, accounting for the uncertainty of emissions reductions to more accurately provide upper and lower bounds within the 95 percent confidence interval, will be investigated. EPA also intends to investigate improvements to its estimates of emissions from hydraulic fracturing, including revisiting the estimates for workover frequency.

In the storage sector, the emission factors calculated in the Inventory account for flashing emissions from condensate tanks. Measurement studies and anecdotal evidence suggest that in some cases produced gas from the separator will bypass the liquid dump valve and vent through the storage tank, which is not taken into account in the current estimates. New data will be reviewed as it becomes available on this emissions source and emissions will be updated, as appropriate.

Data collected through EPA's Greenhouse Gas Reporting Program (40 CFR Part 98, Mandatory Reporting of Greenhouse Gases; Final Rule, Subpart W) will be reviewed for potential improvements to the natural gas systems emissions estimates. The rule will collect actual activity data using improved quantification methods from those used in several of the studies which form the basis of this Inventory. Data collection for Subpart W began January 1, 2011 with emissions reporting beginning in 2012. These data will be reviewed for inclusion into a future Inventory to improve the accuracy and reduce the uncertainty of the emission estimates.

As discussed above, EPA has received information and data related to the emissions estimates through the inventory preparation process and the formal public notice and comment process of the proposed oil and gas new source performance standards (NSPS) for VOCs. EPA plans to carefully evaluate this and all other relevant information provided to us. Subsequently, all relevant updates will then be incorporated, as applicable, in the next cycle of the Inventory.

Finally, EPA is also considering improvements to the documentation of the Inventory. EPA is considering including a table matching each emission factor and activity factor with its source or calculation methodology. The purpose of this improvement would be to make the calculation methodologies more transparent. In addition, EPA is considering adding additional tables to the Annex 3.4 to show activity data and emission factors for previous years. EPA also plans on revising the emissions tables in the Annex 3.4 to show voluntary reductions broken out for key emission sources.

3.7. Petroleum Systems (IPCC Source Category 1B2a)

Methane emissions from petroleum systems are primarily associated with 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. Combustion CO_2 emissions from fuels are already accounted for in the Fossil Fuels Combustion source category, and hence have not been taken into account in the Petroleum Systems source category. Total CH_4 and CO_2 emissions from petroleum systems in 2010 were 31.05 Tg CO_2 Eq. (1,478 Gg CH_4) and 0.34 Tg CO_2 (337 Gg), respectively. Since 1990, CH_4 emissions have declined by 11.8 percent, due to industry efforts to reduce emissions and a decline in domestic oil production (see Table 3-42 and Table 3-43). CO_2 emissions have also declined by 14.4 percent since 1990 due to similar reasons (see Table 3-44 and Table 3-45).

Production Field Operations. Production field operations account for 98 .4 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from field operations account for approximately 90 percent of the emissions from the production sector uncombusted CH_4 emissions (i.e. unburned fuel) account for 6.4 percent, fugitive emissions are 3.5 percent, and process upset emissions are slightly over two-tenths of a percent. The most dominant sources of emissions, in order of magnitude, are shallow water offshore oil platforms, natural-gas-powered high bleed pneumatic devices, oil tanks, natural-gas powered low bleed pneumatic devices, gas engines, deep water offshore platforms, and chemical injection pumps. These seven sources alone emit about 94 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 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 25 percent of such pumps that use associated gas to drive pneumatic pumps. The remaining six 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.

Vented CO_2 associated with natural gas emissions from field operations account for 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 emissions are oil tanks, high bleed pneumatic devices, shallow water offshore oil platforms, low bleed pneumatic devices, and chemical injection pumps. These five sources together account for 98.5 percent of the non-combustion CO_2 emissions from production field operations, while the remaining 1.5 percent of the emissions is distributed among 24 additional activities within the three categories: vented, fugitive and process upsets.

Crude Oil Transportation. Crude oil transportation activities account for less than 0.5 percent of total CH_4 emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for 60.3 percent of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for 18.5 percent. The remaining 21 percent is distributed among six additional sources within these two categories. Emissions from pump engine drivers and heaters were not estimated due to lack of data.

Crude Oil Refining. Crude oil refining processes and systems account for less than 1.5 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, vented emissions account for about 81 percent of the emissions, while fugitive and combustion emissions account for approximately nine and nine and half percent respectively. Refinery system blowdowns for maintenance and the process of asphalt blowing—with air, to harden the asphalt—are the primary venting contributors. Most of the fugitive CH_4 emissions from refineries are from leaks in the fuel gas system. Refinery combustion emissions include small amounts of unburned CH_4 in process heater stack emissions and unburned CH_4 in engine exhausts and flares.

Asphalt blowing from crude oil refining accounts for 4.5 percent of the total non-combustion CO_2 emissions in petroleum systems.

Table 3-42: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	1990	2000	2006	2007	2008	2009	2010
Production Field Operations	**34.7**	**30.8**	**28.7**	**29.3**	**29.5**	**30.2**	**30.6**
Pneumatic device venting	10.3	9.0	8.3	8.4	8.7	8.8	8.8
Tank venting	5.3	4.5	3.9	4.0	3.8	4.3	4.5
Combustion & process upsets	1.9	1.6	1.5	1.5	1.6	2.0	2.0
Misc. venting & fugitives	16.8	15.3	14.5	15.0	14.8	14.6	14.7
Wellhead fugitives	0.6	0.5	0.4	0.4	0.5	0.5	0.5
Crude Oil Transportation	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Refining	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**35.2**	**31.3**	**29.2**	**29.8**	**30.0**	**30.7**	**31.1**

Note: Totals may not sum due to independent rounding.

Table 3-43: CH_4 Emissions from Petroleum Systems (Gg)

Activity	1990	2000	2006	2007	2008	2009	2010
Production Field Operations	**1,653**	**1,467**	**1,365**	**1,396**	**1,404**	**1,437**	**1,455**
Pneumatic device venting	489	428	396	398	416	419	420
Tank venting	250	214	188	192	182	206	214
Combustion & process upsets	88	76	71	72	75	94	97
Misc. venting & fugitives	799	726	692	714	706	693	700
Wellhead fugitives	26	22	17	20	24	24	24
Crude Oil Transportation	**7**	**5**	**5**	**5**	**5**	**5**	**5**
Refining	**18**	**19**	**19**	**19**	**19**	**18**	**19**
Total	**1,677**	**1,492**	**1,389**	**1,420**	**1,427**	**1,460**	**1,478**

Note: Totals may not sum due to independent rounding.

Table 3-44: CO_2 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Activity	1990	2000	2006	2007	2008	2009	2010
Production Field Operations	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Pneumatic device venting	+	+	+	+	+	+	+
Tank venting	0.3	0.3	0.2	0.3	0.2	0.3	0.3
Misc. venting & fugitives	+	+	+	+	+	+	+
Wellhead fugitives	+	+	+	+	+	+	+
Crude Refining	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.01**	**0.02**
Total	**0.39**	**0.34**	**0.31**	**0.31**	**0.30**	**0.33**	**0.34**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-45: CO_2 Emissions from Petroleum Systems (Gg)

Activity	1990	2000	2006	2007	2008	2009	2010
Production Field Operations	**376**	**323**	**285**	**292**	**280**	**311**	**322**
Pneumatic device venting	27	24	22	22	23	23	23
Tank venting	328	281	246	252	239	270	281
Misc. venting & fugitives	18	17	16	16	16	16	16
Wellhead fugitives	1	1	1	1	1	1	1
Crude Refining	**18**	**21**	**20**	**18**	**16**	**14**	**15**
Total	**394**	**344**	**306**	**310**	**297**	**325**	**337**

Note: Totals may not sum due to independent rounding.

Methodology

The methodology for estimating CH_4 emissions from petroleum systems is a bottom-up approach, based on comprehensive studies of CH_4 emissions from U.S. petroleum systems (EPA 1996, EPA 1999). These studies combined emission estimates from 64 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 20 for refining operations. Annex 3.5 provides greater detail on the emission estimates for these 64 activities. The estimates of CH_4 emissions from petroleum systems do not include emissions downstream of oil refineries because these emissions are negligible.

The methodology for estimating CH_4 emissions from the 64 oil industry activities employs emission factors initially developed by EPA (1999). Activity data for the years 1990 through 2010 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 over a one-year period for all federal offshore platforms (EPA 2005, BOEMRE 2004). 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 2010. 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, Regulation, and Enforcement (BOEMRE) (formerly Minerals Management Service) statistics (BOEMRE 2011a-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 2010).

For some years, complete activity data were not available. In such cases, one of three approaches was employed. Where appropriate, the activity data was 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 was held constant from 1990 through 2010 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.

Key references used to obtain activity data are the Energy Information Administration annual and monthly reports (EIA 1990 through 2010, 1995 through 2010, 1995 through 2010a-b), "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 reports (BOEMRE 2005, 2010a-c), analysis of BOEMRE data (EPA 2005, BOEMRE 2004), the Oil & Gas Journal (OGJ 2011a,b), the Interstate Oil and Gas Compact Commission (IOGCC 2009, and the United States Army Corps of Engineers (1995-2009).

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 one activity from petroleum refining. Emissions are estimated for each activity by multiplying emission factors by their corresponding activity data. The emission factors for CO_2 are estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and methane content in produced associated gas. The only exceptions 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).

Uncertainty and Time-Series Consistency

This section describes the analysis conducted to quantify uncertainty associated with the estimates of emissions from petroleum systems. Performed using @RISK software and the IPCC-recommended Tier 2 methodology (Monte Carlo Stochastic Simulation technique), the method employed 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.

The detailed, bottom-up inventory analysis used to evaluate U.S. petroleum systems reduces the uncertainty related to the CH_4 emission estimates in comparison to a top-down approach. However, some uncertainty still remains. Emission factors and activity factors are based on a combination of measurements, equipment design data, engineering calculations and studies, surveys of selected facilities and statistical reporting. Statistical uncertainties arise from natural variation in measurements, equipment types, operational variability and survey and statistical methodologies. Published activity factors are not available every year for all 64 activities analyzed for petroleum systems; therefore, some are estimated. Because of the dominance of the seven major sources, which account for 92 percent of the total methane emissions, the uncertainty surrounding these seven sources has been estimated most rigorously, and serves as the basis for determining the overall uncertainty of petroleum systems emission estimates.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-46. Petroleum systems CH_4 emissions in 2010 were estimated to be between 23.64 and 77.31 Tg CO_2 Eq., while CO_2 emissions were estimated to be between 0.26 and 0.85 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 24 percent below to 149 percent above the 2010 emission estimates of 31.05 and 0.34 Tg CO_2 Eq. for CH_4 and CO_2, respectively.

Table 3-46: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Petroleum Systems	CH_4	31.05	23.64.	77.31	-24%	149%
Petroleum Systems	CO_2	0.34	0.26	0.85	-24%	149%

[a] Range of 2010 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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification Discussion

The petroleum inventory is continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practice. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The primary focus of the QA/QC checks is determining if the assumptions in the Inventory are consistent with current industry practices through regulations, public webcasts, and the Natural Gas STAR Program. Finally, QA/QC checks are consistently conducted to minimize human error in the model calculations.

A webcast was held by EPA for industry to comment on the ratio of high-bleed to low-bleed pneumatics, among other topics. Two of the top seven emission sources, high-bleed and low-bleed pneumatic devices, use the earlier mentioned industry peer review panel activity source (EPA/GRI 1996c). The Inventory assumes four pneumatic devices per well-site with a heater-treater and separator, and three pneumatic devices per well-site with a separator but without a heater-treater. EPA requested industry's views on the assumption that, for each year of the time series (1990 to 2010), 35 percent of devices are high-bleed pneumatic devices. No new information was raised, nor concerns expressed, about this factor during the webcast and therefore this factor has not changed in the current inventory.

Additionally, the webcast discussed the emission factor for a refinery source, asphalt blowing. EPA requested comment on the Inventory's current methane emission factor for asphalt blowing (derived from a Radian International Study) versus the 2009 API Compendium's methane emission factor. The emission factor from the current inventory remained the same for the 2010 Inventory update cycle, however the activity for asphalt blowing was modified by applying a 10 percent factor to the activity obtained through EIA's Petroleum Supply Annual. This was based on asphalt market analysis.

Recalculations Discussion

Most revisions for the current Inventory relative to the previous report were due to updating previous years' data with revised data from existing data sources. Well completion venting, well drilling, and offshore platform activity factors were updated with revised data from existing data sources from 1990 onward. Updating the activity data for asphalt blowing reduced CH_4 and CO_2 emissions for this source by a factor of 10, which has a relatively large impact on fugitive emissions from petroleum refineries, but due to the small contribution of refineries to the overall fugitive emissions, a relatively small impact on the overall GHG emissions estimates from petroleum systems.

In addition, when activity data updates are made for a particular emissions source the entire time series is revised or corrected, which may result in slight changes in estimated emissions from past years..

Planned Improvements

In 2010, all U.S. petroleum refineries were required to collect information on their greenhouse gas emissions. This data was reported to EPA through its Greenhouse Gas Reporting Program in 2011. Data collected under this program will be evaluated for use in future inventories to improve the calculation of national emissions from petroleum systems. In particular, EPA will investigate whether certain emissions sources currently accounted for in the Energy sector should be separately accounted for in the petroleum systems inventory (e.g., CO_2 process emissions from hydrogen production).

EPA is also considering improvements to the documentation of the Inventory. EPA is considering including a table matching each emission factor and activity factor with its source or calculation methodology. The purpose of this improvement would be to make the calculation methodologies more transparent.

[BEGIN BOX]

Box 3-3: 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 current Inventory, emissions from naturally-produced CO_2 are estimated based on the application.

In the current Inventory report, the 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 (IPCC, 2006) included, for the first time, 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.

As of January 1, 2011, facilities that conduct geologic sequestration of CO_2 and all other facilities that inject CO_2 underground are required to calculate and report greenhouse gas data annually to EPA through its Greenhouse Gas Reporting Program. The Greenhouse Gas Reporting Program requires greenhouse gas reporting from facilities that inject CO_2 underground for geologic sequestration, and requires greenhouse gas reporting from all other facilities that inject CO_2 underground for any reason, including enhanced oil and gas recovery. Facilities conducting geologic sequestration of CO_2 are required to develop and implement an EPA-approved site-specific monitoring, reporting and verification (MRV) plan, and to report the amount of CO_2 sequestered using a mass balance approach. Data from this program, which will be reported to EPA starting in 2012, for the 2011 calendar year, will provide additional facility-specific information about the carbon capture, transport and storage chain, EPA intends to evaluate that information closely and consider opportunities for improving our current inventory estimates.

Preliminary estimates indicate that the amount of CO_2 captured from industrial and natural sites is 46.2 Tg CO_2 (47,198 Gg CO_2) (see Table 3-47and Table 3-48). 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.

Table 3-47: Potential Emissions from CO_2 Capture and Transport (Tg CO_2 Eq.)

Year	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Acid Gas Removal Plants	4.8	2.3	5.8	6.2	6.4	6.6	7.0	11.6
Naturally Occurring CO_2	20.8	23.2	28.3	30.2	33.1	36.1	39.7	34.0
Ammonia Production Plants	+	0.7	0.7	0.7	0.7	0.6	0.6	0.7
Pipelines Transporting CO_2	+	+	+	+	+	+	+	+
Total	**25.6**	**26.1**	**34.7**	**37.1**	**40.1**	**43.3**	**47.3**	**46.2**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note; Totals may not sum due to independent rounding.

Table 3-48: Potential Emissions from CO_2 Capture and Transport (Gg)

Year	1990	2000	2005	2006	2007	2008	2009	2010
Acid Gas Removal Plants	4,832	2,264	5,798	6,224	6,088	6,630	7,035	11,554
Naturally Occurring CO_2	20,811	23,208	28,267	30,224	33,086	36,102	39,725	33,967
Ammonia Production Plants	+	676	676	676	676	580	580	677
Pipelines Transporting CO_2	8	8	7	7	7	8	8	8
Total	**25,643**	**26,149**	**34,742**	**37,124**	**40,141**	**43,311**	**47,340**	**46,198**

+ Does not exceed 0.5 Gg.
Note: Totals do not include emissions from pipelines transporting CO_2
Note; Totals may not sum due to independent rounding.

[END BOX]

3.8. Energy Sources of Indirect Greenhouse Gas Emissions – TO BE UPDATED

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 2009 are reported in Table 3-49.

Table 3-49: NO_x, CO, and NMVOC Emissions from Energy-Related Activities (Gg)

Gas/Source	1990	2000	2005	2006	2007	2008	2009
NO_x	**21,106**	**18,477**	**15,319**	**14,473**	**13,829**	**13,012**	**10,887**
Mobile Combustion	10,862	10,199	9,012	8,488	7,965	7,441	6,206
Stationary Combustion	10,023	8,053	5,858	5,545	5,432	5,148	4,159
Oil and Gas Activities	139	111	321	319	318	318	393
Incineration of Waste	82	114	129	121	114	106	128
*International Bunker Fuels**	*2,020*	*1,344*	*1,703*	*1,793*	*1,791*	*1,917*	*1,651*
CO	**125,640**	**89,714**	**69,062**	**65,399**	**61,739**	**58,078**	**49,647**
Mobile Combustion	119,360	83,559	62,692	58,972	55,253	51,533	43,355
Stationary Combustion	5,000	4,340	4,649	4,695	4,744	4,792	4,543
Incineration of Waste	978	1,670	1,403	1,412	1,421	1,430	1,403
Oil and Gas Activities	302	146	318	319	320	322	345
*International Bunker Fuels**	*130*	*128*	*132*	*161*	*160*	*165*	*149*
NMVOCs	**12,620**	**8,952**	**7,798**	**7,702**	**7,604**	**7,507**	**5,333**
Mobile Combustion	10,932	7,229	6,330	6,037	5,742	5,447	4,151
Stationary Combustion	912	1,077	716	918	1,120	1,321	424
Oil and Gas Activities	554	388	510	510	509	509	599
Incineration of Waste	222	257	241	238	234	230	159
*International Bunker Fuels**	*61*	*45*	*54*	*59*	*59*	*62*	*57*

* These values are presented for informational purposes only and are not included in totals.
Note: Totals may not sum due to independent rounding.

Methodology

These emission estimates were obtained from preliminary data (EPA 2010, EPA 2009), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. 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 categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

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 2009. 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.[103] 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).[104]

Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O. Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[105] 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.[106]

Emissions of CO_2 from aircraft are essentially a function of fuel use. Methane and N_2O emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Methane is the product of incomplete combustion and occurs mainly during the landing and take-off phases. 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

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[103] 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).

[104] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[105] 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).

[106] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

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 2010 from the combustion of international bunker fuels from both aviation and marine activities were 126.0 Tg CO_2 Eq., or 11 percent above emissions in 1990 (see Table 3-50 and Table 3-51). Emissions from international flights and international shipping voyages departing from the United States have increased by 49 percent and decreased by 15 percent, respectively, since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 and N_2O were also emitted.

Table 3-50: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (Tg CO_2 Eq.)

Gas/Mode	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**111.8**		**109.7**	**128.4**	**127.6**	**133.7**	**123.1**	**124.7**
Aviation	46.4		56.7	74.6	73.8	75.5	69.4	69.4
Marine	65.4		53.0	53.8	53.9	58.2	53.7	55.3
CH_4	**0.2**		**0.1**	**0.2**	**0.2**	**0.2**	**0.1**	**0.2**
Aviation	+		+	+	+	+	+	+
Marine	0.1		0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**1.1**		**1.0**	**1.2**	**1.2**	**1.2**	**1.1**	**1.1**
Aviation	0.5		0.6	0.8	0.8	0.8	0.7	0.7
Marine	0.5		0.4	0.4	0.4	0.5	0.4	0.4
Total	**113.0**		**110.9**	**129.7**	**129.0**	**135.1**	**124.4**	**126.0**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-51: CO_2, CH_4 and N_2O Emissions from International Bunker Fuels (Gg)

Gas/Mode	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**111,828**		**109,750**	**128,384**	**127,618**	**133,704**	**123,127**	**124,702**
Aviation	46,399		56,736	74,552	73,762	75,508	69,404	69,404
Marine	65,429		53,014	53,832	53,856	58,196	53,723	55,299
CH_4	**8**		**7**	**8**	**8**	**8**	**7**	**8**
Aviation	2		2	2	2	2	2	2
Marine	7		5	5	5	6	5	6
N_2O	**3**		**3**	**4**	**4**	**4**	**4**	**4**
Aviation	2		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.

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. C 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 3.7 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 (2010) and USAF (1998), and heat content for jet fuel was taken from EIA (2010a). A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.7 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the Revised 1996 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1997). For aircraft emissions, the following values, in units of grams of pollutant per kilogram of fuel consumed (g/kg), were employed: 0.09 for CH_4 and 0.1 for N_2O 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 aircraft fuel consumption for inventory years 2000 through 2005 were developed using the FAA's System for assessing Aviation's Global Emissions (SAGE) model (FAA 2006). That tool has been subsequently replaced by the Aviation Environmental Design Tool (AEDT), which calculates noise in addition to aircraft fuel burn and emissions for flights globally in a given year (FAA 2010). Data for inventory years 2006 through 2009 were developed using AEDT. Data for 2010 were proxied to 2009 as AEDT data will not be available until Public Review.

International aviation bunker fuel consumption from 1990 to 2010 was calculated by assigning the difference between the sum of domestic activity data (in Tbtu) from SAGE and the AEDT, and the reported EIA transportation jet fuel consumption to the international bunker fuel category for jet fuel from EIA (2010a). 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 by the Defense Energy Support Center, under DoD's Defense Logistics Agency (DESC 2011). 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 3-52. See Annex 3.7 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 2010, 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 DESC (2011). The total amount of fuel provided to naval vessels was reduced by 13 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 3-53.

Table 3-52: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990		2005	2006	2007	2008	2009	2010
U.S. and Foreign Carriers	4,934		5,943	7,809	7,726	7,909	7,270	7,270
U.S. Military	862		464	403	413	389	370	359
Total	**5,796**		**6,407**	**8,212**	**8,139**	**8,298**	**7,640**	**7,628**

Note: Totals may not sum due to independent rounding.

Table 3-53: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990		2005	2006	2007	2008	2009	2010
Residual Fuel Oil	4,781		3,881	4,004	4,059	4,373	4,040	4,141
Distillate Diesel Fuel & Other	617		444	446	358	445	426	476
U.S. Military Naval Fuels	522		471	414	444	437	384	377
Total	**5,920**		**4,796**	**4,864**	**4,861**	**5,254**	**4,850**	**4,994**

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.[107] 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 Revised 1996 IPCC Guidelines is to use data by specific aircraft type (IPCC/UNEP/OECD/IEA 1997). 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.[108]

There is also concern regarding the reliability of the existing DOC (1991 through 2010) 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 2009. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification – TO BE UDPATED

A source-specific QA/QC plan for international bunker fuels was developed and implemented. This effort included

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[107] See uncertainty discussions under Carbon Dioxide Emissions from Fossil Fuel Combustion.

[108] 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.

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 – TO BE UDPATED

Slight changes to emission estimates are due to revisions made to historical activity data for aviation jet fuel consumption using the FAA's AEDT. These historical data changes resulted in changes to the emission estimates for 1990 through 2008 relative to the previous inventory, which averaged to an annual decrease in emissions from international bunker fuels of 0.13 Tg CO_2 Eq. (0.1 percent) in CO_2 emissions, an annual decrease of less than 0.01 Tg CO_2 Eq. (0.05 percent) in CH_4 emissions, and an annual decrease of less than 0.01 Tg CO_2 Eq. (0.1 percent) in N_2O emissions.

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 from corn and woody crops 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 7), 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 2010, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 191.6 Tg CO_2 Eq. (191,591 Gg) (see Table 3-54 and Table 3-55). As the largest consumer of woody biomass, the industrial sector was responsible for 70 percent of the CO_2 emissions from this source. Emissions from this sector increased from 2009 to 2010 due to a corresponding increase in wood consumption. The residential sector was the second largest emitter, constituting 25 percent of the total, while the commercial and electricity generation sectors accounted for the remainder.

Table 3-54: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990		2005	2006	2007	2008	2009	2010
Industrial	143.2		148.4	150.0	143.9	136.3	122.9	133.9
Residential	63.3		48.3	43.7	48.1	50.1	48.4	47.3
Commercial	7.2		7.8	7.2	7.8	8.1	8.2	7.9
Electricity Generation	0.7		1.2	1.7	2.4	2.8	2.4	2.6
Total	**214.4**		**205.7**	**202.7**	**202.2**	**197.4**	**181.8**	**191.6**

Note: Totals may not sum due to independent rounding.

Table 3-55: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990		2005	2006	2007	2008	2009	2010
Industrial	143,219		148,386	150,033	143,929	136,324	122,851	133,871
Residential	63,286		48,283	43,657	48,113	50,147	48,440	47,260
Commercial	7,173		7,821	7,246	7,768	8,133	8,160	7,908
Electricity Generation	733		1,182	1,744	2,394	2,754	2,355	2,552
Total	**214,410**		**205,671**	**202,680**	**202,204**	**197,358**	**181,806**	**191,591**

Note: Totals may not sum due to independent rounding.

Biomass-derived fuel consumption in the United States transportation sector consisted primarily of ethanol use. Ethanol is primarily produced from corn grown in the Midwest, and was used mostly in the Midwest and South. Pure ethanol can be combusted, or it can be mixed with gasoline as a supplement or octane-enhancing agent. The most common mixture is a 90 percent gasoline, 10 percent ethanol blend known as gasohol. Ethanol and ethanol blends are often used to fuel public transport vehicles such as buses, or centrally fueled fleet vehicles.

In 2010, the United States consumed an estimated 1,089 trillion Btu of ethanol, and as a result, produced approximately 74.5 Tg CO_2 Eq. (74,519 Gg) (see Table 3-56 and Table 3-57) of CO_2 emissions. Ethanol production and consumption has grown steadily every year since 1990, with the exception of 1996 due to short corn supplies and high prices in that year.

Table 3-56: CO_2 Emissions from Ethanol Consumption (Tg CO_2 Eq.)

End-Use Sector	1990	2005	2006	2007	2008	2009	2010
Transportation	4.1	22.4	30.2	38.1	53.8	61.2	73.2
Industrial	0.1	0.5	0.7	0.7	0.8	0.9	1.1
Commercial	+	0.1	0.1	0.1	0.1	0.2	0.2
Total	**4.2**	**22.9**	**31.0**	**38.9**	**54.7**	**62.3**	**74.5**

+ Does not exceed 0.05 Tg CO_2 Eq.

Table 3-57: CO_2 Emissions from Ethanol Consumption (Gg)

End-Use Sector	1990	2005	2006	2007	2008	2009	2010
Transportation[a]	4,136	22,414	30,237	38,116	53,796	61,191	73,225
Industrial	56	468	662	674	797	888	1,062
Commercial	34	60	86	135	146	194	232
Total	**4,227**	**22,943**	**30,985**	**38,924**	**54,739**	**62,272**	**74,519**

[a] See Annex 3.2, Table A-88 for additional information on transportation consumption of these fuels.

Methodology

Woody biomass emissions were estimated by applying two EIA gross heat contents (Lindstrom 2006) to U.S. consumption data (see Table 3-58), provided in energy units. This year woody biomass consumption data for the industrial, residential, and commercial sectors were obtained from EIA 2011, while woody biomass consumption data for the electricity generation sector was estimated from EPA's Clean Air Market Acid Rain Program dataset (EPA 2011). The bottom-up analysis of woody biomass consumption based on EPA's Acid Rain Program dataset indicated that the amount of woody biomass consumption allocated in the EIA statistics should be adjusted. Therefore, for these estimates, the electricity generation sector's woody biomass consumption was adjusted downward to match the value obtained from the bottom-up analysis based on EPA's Acid Rain Program dataset. As the total woody biomass consumption estimate from EIA is considered to be accurate at the national level, the woody biomass consumption totals for the industrial, residential, and commercial sectors were adjusted upward proportionately.

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 Tg C/QBtu (EPA 2010) to U.S. ethanol consumption estimates that were provided in energy units (EIA 2011) (see Table 3-59).

Table 3-58: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2006	2007	2008	2009	2010
Industrial	1,525.8	1,580.8	1,598.4	1,533.3	1,452.3	1,308.8	1,426.2
Residential	613.7	468.2	423.4	466.6	486.3	469.8	458.3
Commercial	69.6	75.8	70.3	75.3	78.9	79.1	76.7
Electricity Generation	7.1	11.5	16.9	23.2	26.7	22.8	24.7
Total	**2,216.2**	**2,136.4**	**2,108.9**	**2,098.5**	**2,044.2**	**1,880.5**	**1,985.9**

Table 3-59: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990		2005	2006	2007	2008	2009	2010
Transportation	60.4		327.4	441.7	556.8	785.8	893.9	1,069.7
Industrial	0.8		6.8	9.7	9.8	11.6	13.0	15.5
Commercial	0.5		0.9	1.3	2.0	2.1	2.8	3.4
Total	**61.7**		**335.1**	**452.6**	**568.6**	**799.6**	**909.7**	**1,088.6**

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 2009. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Wood and ethanol consumption values were revised relative to the previous Inventory for 2009 based on updated information from EIA's Annual Energy Review (EIA 2011). Additionally, the change in methodology for calculating emissions from woody biomass led a decrease in emissions from the electricity generation sector and an increase in emissions for the other sectors over the time series. This adjustment of historical data for wood biomass consumption resulted in an average annual decrease in emissions from wood biomass consumption of about 1.0 Tg CO_2 Eq. (0.5 percent) from 1990 through 2009. Slight adjustments were made to ethanol consumption based on updated information from EIA (2011), which slightly increased estimates for ethanol consumed. As a result of adjustments to historical EIA data, average annual emissions from ethanol consumption increased by less than 0.05 Tg CO_2 Eq. (less than 0.05 percent) relative to the previous Inventory.

Planned Improvements

The availability of facility-level combustion emissions through EPA's Greenhouse Gas Reporting Program (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,[109] some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions. In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes 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

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

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.[110]

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

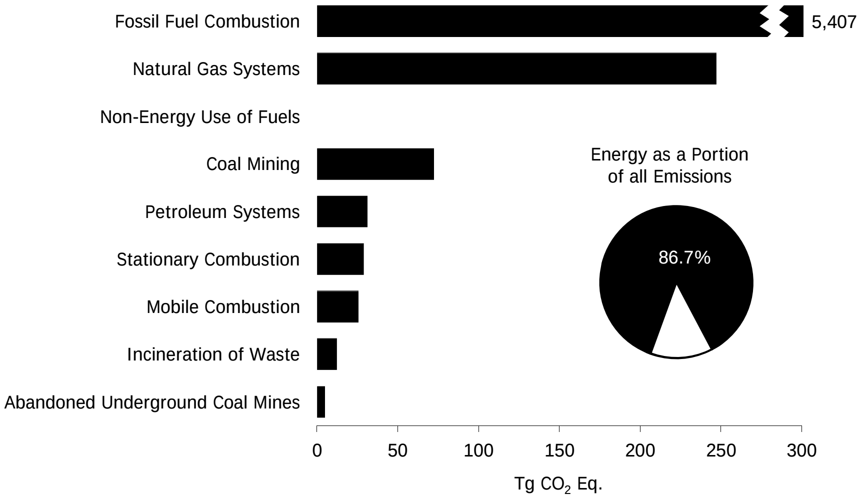

Figure 3-1: 2010 Energy Chapter Greenhouse Gas Sources

To be provided:

Figure 3-2: 2010 U.S. Fossil Carbon Flows (Tg CO2 Eq.)

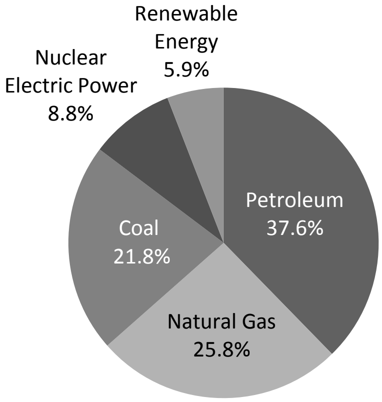

Figure 3-3: 2010 U.S. Energy Consumption by Energy Source

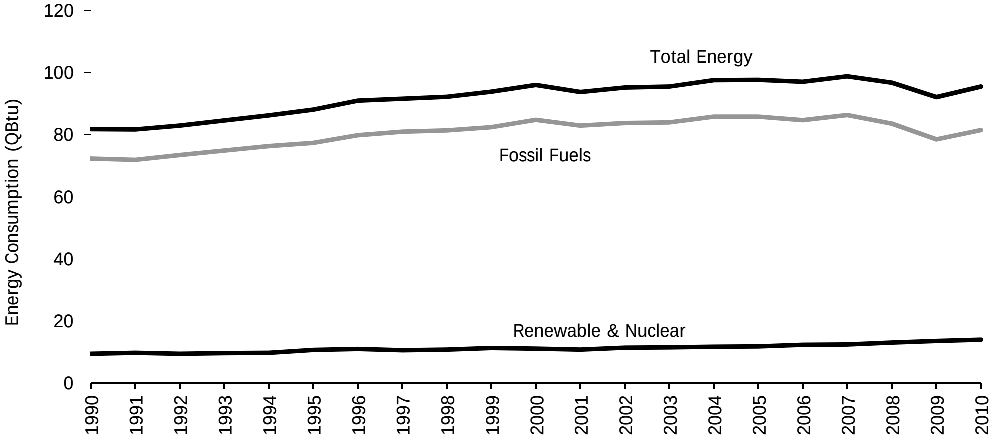

Figure 3-4: U.S. Energy Consumption (Quadrillion Btu)

Note: Expressed as gross calorific values.

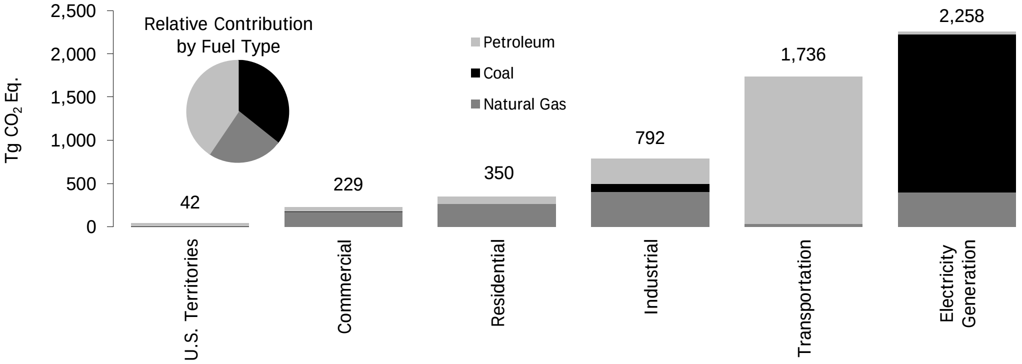

Figure 3-5: 2010 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

Note: The electricity generation sector also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.

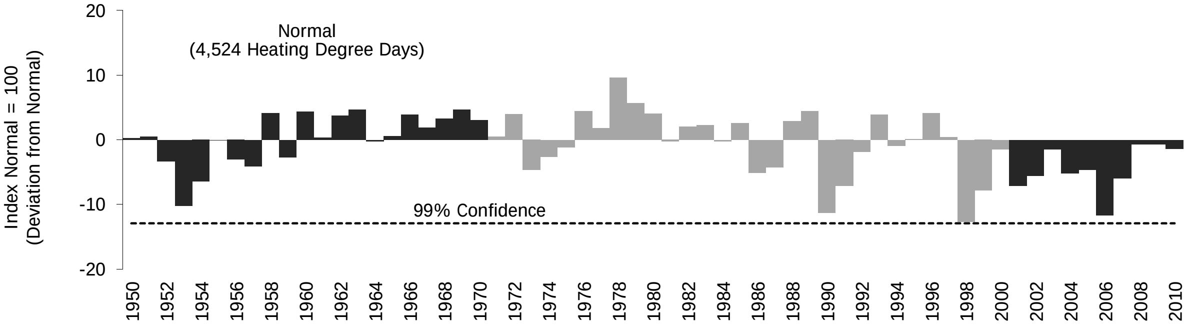

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1950-2010)

Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1971 through 2000.

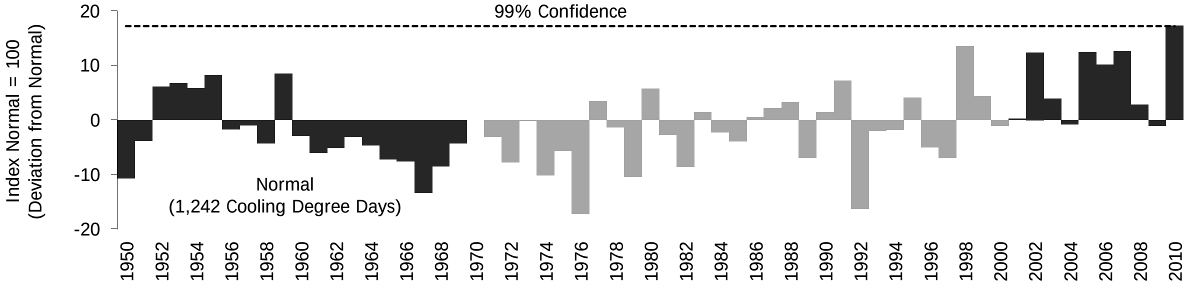

Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950-2010)

Note: Climatological normal data are highlighted.
Statistical confidence interval for "normal" climatology period of 1971 through 2000.

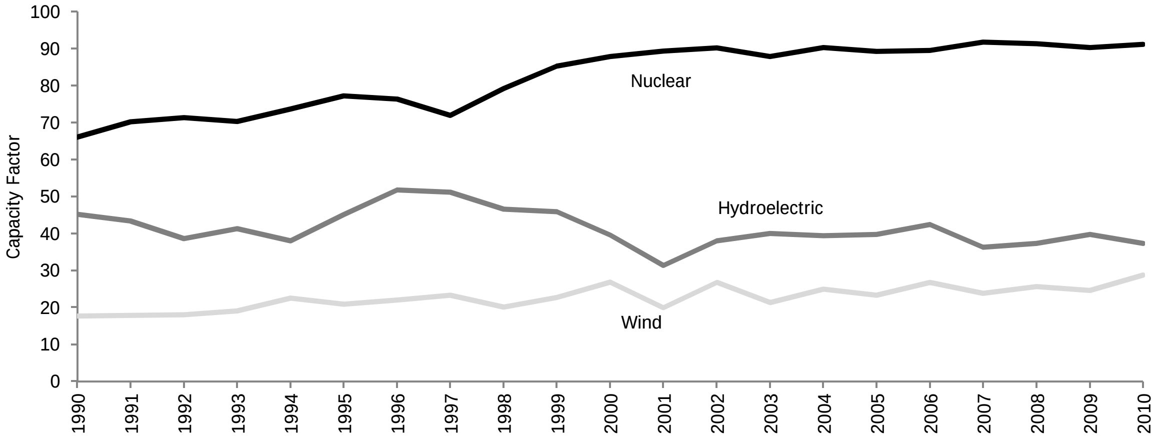

Figure 3-8: Nuclear, Hydroelectric, and Wind Power Plant Capacity Factors in the United States (1990-2010)

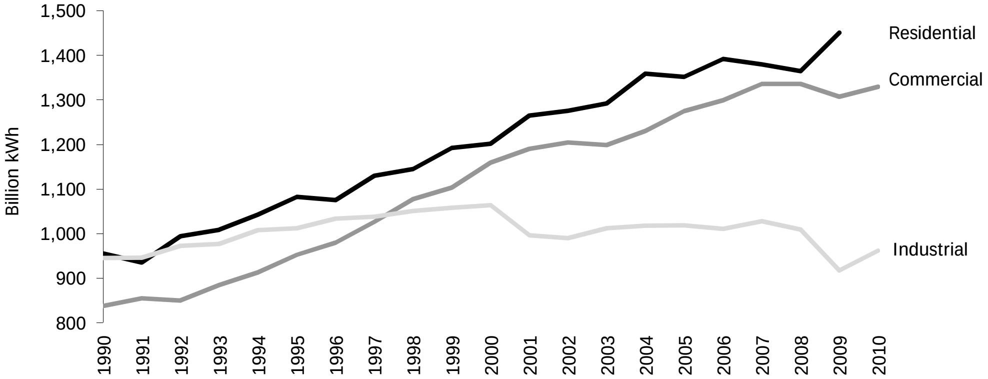

Figure 3-9: Electric Generation Retail Sales by End-Use Sector

Note: The transportation end-use sector consumes minor quanties of electricity.

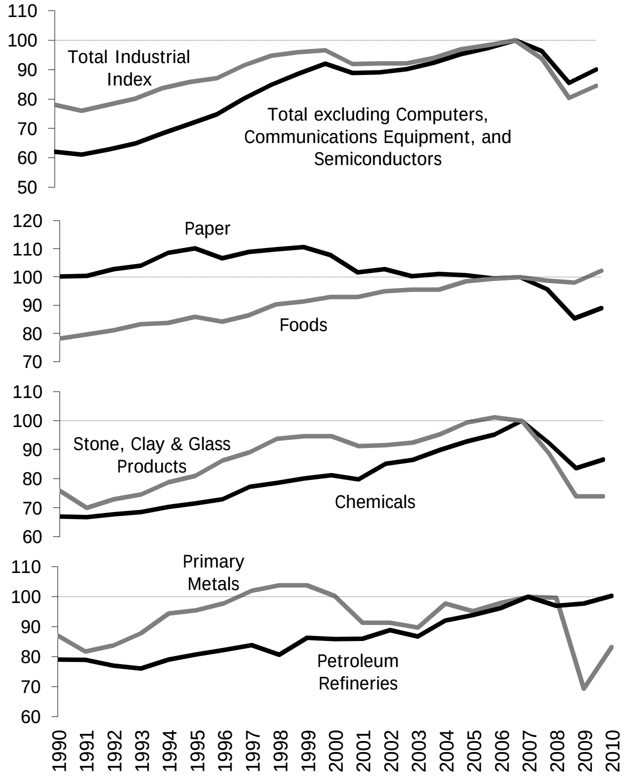

Figure 3-10: Industrial Production Indexes (Index 2007=100)

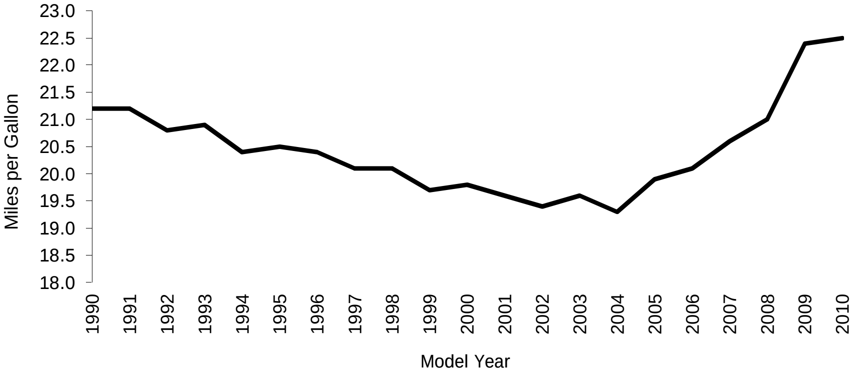

Figure 3-11: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990-2010

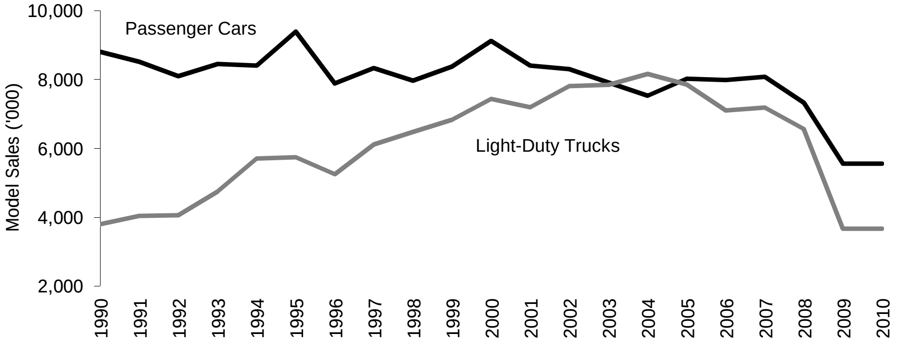

Figure 3-12: Sales of New Passenger Cars and Light-Duty Trucks, 1990-2010

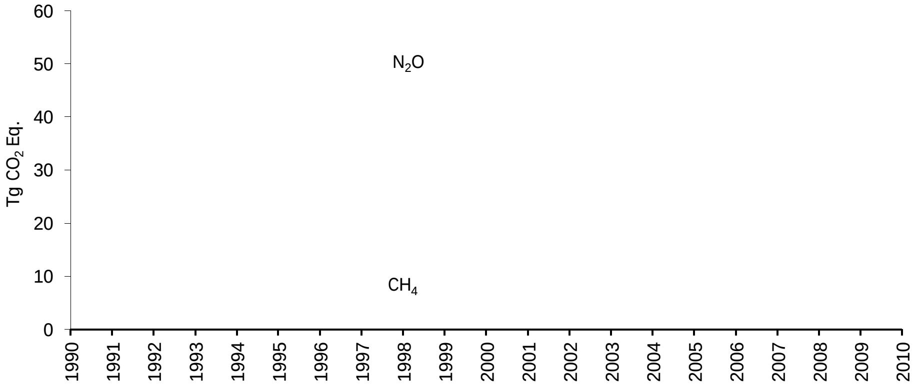

Figure 3-13: Mobile Source CH_4 and N_2O Emissions

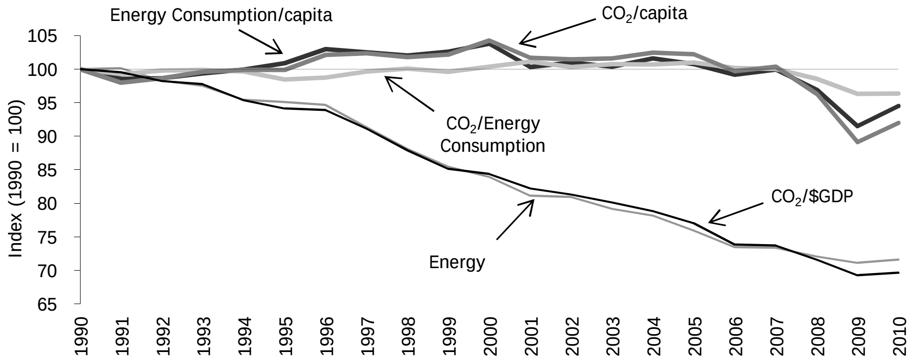

Figure 3-14: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP

4. Industrial Processes

Greenhouse gas emissions are produced as the by-products of various non-energy-related industrial activities. That is, these emissions are produced from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically 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 addressed in this chapter include iron and steel production and metallurgical coke production, cement production, lime production, ammonia production and urea consumption, limestone and dolomite consumption (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and use, aluminum production, titanium dioxide production, CO_2 consumption, ferroalloy production, phosphoric acid production, zinc production, lead production, petrochemical production, silicon carbide production and consumption, nitric acid production, and adipic acid production (see Figure 4-1).

Figure 4-1: 2010 Industrial Processes Chapter Greenhouse Gas Sources

In addition to the three greenhouse gases listed above, there are also industrial sources of man-made fluorinated compounds called hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The present contribution of these 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. Usage 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. In addition to their use as ODS substitutes, HFCs, PFCs, and SF_6 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.

In 2010, industrial processes generated emissions of 315.4teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 4.6 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 139.2 Tg CO_2 Eq. (139,533Gg) in 2010, or 2.4 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 1.5 Tg CO_2 Eq. (69 Gg) in 2010, which was less than 1 percent of U.S. CH_4 emissions. N_2O emissions from adipic acid and nitric acid production were 19.5 Tg CO_2 Eq. (63 Gg) in 2010, or 6.0 percent of total U.S. N_2O emissions. In 2010 combined emissions of HFCs, PFCs, and SF_6 totaled 154.8 Tg CO_2 Eq. Total emissions from Industrial Processes in 2010 were roughly equal to 1990 emissions.

Table 4-1 summarizes emissions for the Industrial Processes chapter in Tg CO_2 Eq., while unweighted native gas emissions in Gg are provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the common reporting format tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, and SF_6.

Table 4-1: Emissions from Industrial Processes (Tg CO_2 Eq.)

Gas/Source	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**188.5**	**165.4**	**169.9**	**172.6**	**159.5**	**118.1**	**139.5**
Iron and Steel Production and Metallurgical Coke Production	99.6	66.0	68.9	71.1	66.1	42.1	54.3
Iron and Steel Production	97.1	64.0	66.9	69.1	63.8	41.2	52.2
Metallurgical Coke Production	2.5	2.0	1.9	2.1	2.3	1.0	2.1
Cement Production	33.3	45.2	45.8	44.5	40.5	29.0	30.5
Lime Production	11.5	14.4	15.1	14.6	14.3	11.2	13.2
Limestone and Dolomite Use	5.1	6.8	8.0	7.7	6.3	7.6	10.0
Ammonia Production	13.0	9.2	8.8	9.1	7.9	7.9	8.7
Urea Consumption for Non-Ag Purposes	3.8	3.7	3.5	4.9	4.1	3.4	4.4

Soda Ash Production and Consumption	4.1	4.2	4.2	4.1	4.1	3.6	3.7
Petrochemical Production	3.3	4.2	3.8	3.9	3.4	2.7	3.3
Aluminum Production	6.8	4.1	3.8	4.3	4.5	3.0	3.0
Carbon Dioxide Consumption	1.4	1.3	1.7	1.9	1.8	1.8	2.2
Titanium Dioxide Production	1.2	1.8	1.8	1.9	1.8	1.6	1.9
Ferroalloy Production	2.2	1.4	1.5	1.6	1.6	1.5	1.5
Zinc Production	0.6	1.0	1.0	1.0	1.2	0.9	1.2
Phosphoric Acid Production	1.5	1.4	1.2	1.2	1.2	1.0	1.0
Lead Production	0.5	0.6	0.6	0.6	0.6	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.1	0.2
CH_4	**1.9**	**1.8**	**1.7**	**1.7**	**1.6**	**1.2**	**1.5**
Petrochemical Production	0.9	1.1	1.0	1.0	0.9	0.8	0.9
Iron and Steel Production and Metallurgical Coke Production	1.0	0.7	0.7	0.7	0.6	0.4	0.5
Iron and Steel Production	1.0	0.7	0.7	0.7	0.6	0.4	0.5
Metallurgical Coke Production	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
N_2O	**33.1**	**23.6**	**24.8**	**29.6**	**18.7**	**17.1**	**19.5**
Nitric Acid Production	17.4	16.2	15.9	18.9	16.1	14.3	16.7
Adipic Acid Production	15.8	7.4	8.9	10.7	2.6	2.8	2.8
HFCs	**36.9**	**120.2**	**123.4**	**129.5**	**129.4**	**125.7**	**135.4**
Substitution of Ozone Depleting Substances[a]	0.3	104.2	109.3	112.3	115.5	120.0	129.7
HCFC-22 Production	36.4	15.8	13.8	17.0	13.6	5.4	5.4
Semiconductor Manufacturing HFCs	0.2	0.2	0.3	0.3	0.3	0.3	0.3
PFCs	**20.6**	**6.2**	**6.0**	**7.5**	**6.7**	**5.6**	**5.6**
Semiconductor Manufacturing PFCs	2.2	3.1	3.4	3.6	3.8	4.0	4.0
Aluminum Production	18.4	3.0	2.5	3.8	2.7	1.6	1.6
SF_6	**32.6**	**17.8**	**16.8**	**15.6**	**15.0**	**13.9**	**13.8**
Electrical Transmission and Distribution	26.7	13.9	13.0	12.2	12.2	11.8	11.8
Magnesium Production and Processing	5.4	2.9	2.9	2.6	1.9	1.1	1.1
Semiconductor Manufacturing SF_6	0.5	1.0	1.0	0.8	0.9	1.0	1.0
Total	**313.7**	**335.1**	**342.7**	**356.5**	**330.8**	**281.6**	**315.4**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

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

Table 4-2: Emissions from Industrial Processes (Gg)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CO_2	**188,460**	**165,402**	**169,895**	**172,609**	**159,462**	**118,105**	**139,533**
Iron and Steel Production and Metallurgical Coke Production	99,593	66,000	68,854	71,138	66,092	42,113	54,276
Iron and Steel Production	97,123	63,957	66,934	69,083	63,758	41,157	52,192
Metallurgical Coke Production	2,470	2,043	1,919	2,055	2,334	956	2,084
Cement Production	33,278	45,197	45,792	44,538	40,531	29,018	30,509
Lime Production	11,533	14,379	15,100	14,595	14,330	11,225	13,151
Limestone and Dolomite Use	5,127	6,768	8,035	7,702	6,276	7,649	10,017

Ammonia Production	13,047	9,196	8,781	9,074	7,883	7,855	8,678
Urea Consumption for Non-Ag Purposes	3,784	3,653	3,519	4,944	4,065	3,415	4,365
Soda Ash Production and Consumption	4,141	4,228	4,162	4,140	4,099	3,554	3,735
Petrochemical Production	3,311	4,181	3,837	3,931	3,449	2,735	3,336
Aluminum Production	6,831	4,142	3,801	4,251	4,477	3,009	3,009
Carbon Dioxide Consumption	1,416	1,321	1,709	1,867	1,780	1,784	2,203
Titanium Dioxide Production	1,195	1,755	1,836	1,930	1,809	1,648	1,876
Ferroalloy Production	2,152	1,392	1,505	1,552	1,599	1,469	1,469
Zinc Production	632	1,030	1,030	1,025	1,159	943	1,168
Phosphoric Acid Production	1,529	1,386	1,167	1,166	1,187	1,018	1,017
Lead Production	516	553	560	562	551	525	542
Silicon Carbide Production and Consumption	375	219	207	196	175	145	181
CH_4	**88**	**86**	**83**	**82**	**74**	**58**	**69**
Petrochemical Production	41	51	48	48	43	39	44
Iron and Steel Production and Metallurgical Coke Production	46	34	35	33	31	17	25
Iron and Steel Production	46	34	35	33	31	17	25
Metallurgical Coke Production	+	+	+	+	+	+	+
Ferroalloy Production	1	+	+	+	+	+	+
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
N_2O	**107**	**76**	**80**	**95**	**60**	**55**	**63**
Nitric Acid Production	56	52	51	61	52	46	54
Adipic Acid Production	51	24	29	34	8	9	9
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	1	+	+
Semiconductor Manufacturing HFCs	+	+	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Semiconductor Manufacturing PFCs	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
SF_6	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Electrical Transmission and Distribution	1	1	1	1	1	+	+
Magnesium Production and Processing	M	M	M	M	M	M	M
Semiconductor Manufacturing SF_6	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg

M (Mixture of gases)

Note: Totals may not sum due to independent rounding.

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

[BEGIN BOX]

Box 4-1: Industrial Processes Data from EPA's 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. For calendar year 2010, the first year in which data were reported, facilities in 29 categories provided in 40 CFR part 98 were required to report their 2010 emissions by the September 30, 2011 reporting deadline.

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. In addition, it should be noted that the definitions and provisions for reporting fuel types in EPA's GHGRP may differ from those used in the national inventory in meeting the UNFCCC reporting guidelines. In line with the UNFCCC reporting guidelines[111], 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 EPA's GHGRP website.[112]

EPA presents the data collected by EPA's GHGRP through a data publication tool[113] that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.

[END BOX]

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.[114] 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 36 states and Puerto Rico. Texas, California, Missouri, Pennsylvania, Alabama, and Michigan were the six largest (in descending order) cement-producing states in 2011 and accounted for approximately half of U.S. production (USGS 2011).

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. 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.[115]

In 2010, U.S. clinker production—including Puerto Rico—totaled 59,000 thousand metric tons (USGS 2011). The resulting CO_2 emissions were estimated to be 30.5 Tg CO_2 Eq. (30,509 Gg) (see Table 4-3).

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

[112] See <http://www.ccdsupport.com/confluence/display/ghgp/Detailed+Description+of+Data+for+Certain+Sources+and+Processes>.

[113] See <http://ghgdata.epa.gov>.

[114] The CO_2 emissions related to the consumption of energy for cement manufacture are accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter.

[115] 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.

Table 4-3: CO_2 Emissions from Cement Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	33.3	33,278
2005	45.2	45,197
2006	45.8	45,792
2007	44.5	44,538
2008	40.5	40,531
2009	29.0	29,018
2010	30.5	30,509

Greenhouse gas emissions from cement production grew every year from 1991 through 2006, but have decreased since. Emissions since 1990 have decreased by eight percent. Emissions decreased significantly between 2008 and 2009, due to the economic recession and associated decrease in demand for construction materials. Although emissions increased slightly from 2009 levels in 2010, they remain 25 percent below 2008 levels, again due to the ongoing contraction of the housing market. 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 from cement production are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone) in the cement kiln. While in the kiln, limestone is broken down into CO_2 and lime, with the CO_2 released to the atmosphere. The quantity of CO_2 emitted during cement production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ (i.e., limestone) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

CO_2 emissions were estimated by applying an emission factor, in tons of CO_2 released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis 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 (van Oss 2008). This calculation yields an emission factor of 0.51 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$EF_{\text{Clinker}} = 0.6460\ \text{CaO} \times \left[\frac{44.01\ \text{g/mole}\text{CO}_2}{56.08\ \text{g/mole}\text{CaO}}\right] = 0.5070\ \text{tons CO}_2/\text{ton clinker}$$

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.[116] 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 (one to two percent) amount 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

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[116] Default IPCC clinker and CKD emission factors were verified through expert consultation with the Portland Cement Association (PCA 2008) and van Oss (2008).

assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006). The 1990 through 2010 activity data for clinker production (see Table 4-4) were obtained from USGS (US Bureau of Mines 1990 through 1993, USGS 1995 through 2011). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants.

Table 4-4: Clinker Production (Gg)

Year	Clinker
1990	64,355
2005	87,405
2006	88,555
2007	86,130
2008	78,382
2009	56,116
2010	59,000

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 2008). 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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-5. 2010 CO_2 emissions from cement production were estimated to be between 26.5 and 34.7 Tg CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 13 percent below and 14 percent above the emission estimate of 30.5 Tg CO_2 Eq.

Table 4-5: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	30.5	26.5	34.7	-13%	+14%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Activity data for the time series was revised for the current Inventory. Specifically, clinker production data for 2006 through 2009 were revised to reflect updated USGS data. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Cement category involve research into the availability of cement 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 Cement 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.[117]

4.2. Lime Production (IPCC Source Category 2A2)

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Its 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. 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•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

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. 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.[118]

Lime production in the United States—including Puerto Rico—was reported to be 18,259 thousand metric tons in 2010 (USGS 2011). This production resulted in estimated CO_2 emissions of 13.2 Tg CO_2 Eq. (13,151 Gg) (see Table 4-6 and Table 4-7).

Table 4-6: CO_2 Emissions from Lime Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	11.5	11,533
2005	14.4	14,379
2006	15.1	15,100
2007	14.6	14,595
2008	14.3	14,330
2009	11.2	11,225
2010	13.2	13,151

Table 4-7: Potential, Recovered, and Net CO_2 Emissions from Lime Production (Gg)

Year	Potential	Recovered*	Net Emissions
1990	12,004	471	11,533
2005	15,131	752	14,379
2006	15,825	725	15,100

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

[118] 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.

2007	15,264	669	14,595
2008	14,977	647	14,330
2009	11,913	688	11,225
2010	13,795	644	13,151

* For sugar refining and PCC production.
Note: Totals may not sum due to rounding

Lime production in 2010 rebounded from a 21 percent decline in 2009 to 18,259 thousand metric tons, which is still eight 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. The contemporary lime market is approximately distributed across five end-use categories as follows: metallurgical uses, 35 percent; environmental uses, 32 percent; chemical and industrial uses, 23 percent; construction uses, nine percent; and refractory dolomite, one percent. Consumption for metallurgical uses, which accounted for 57 percent of the overall decrease in lime consumption in 2009, recorded the most significant (62 percent) gains of 2010 (USGS 2011).

Methodology

During the calcination stage of lime production, CO_2 is given off as a gas and normally exits the system with the stack gas. To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors using a Tier 2 approach. The emission factor is the product of a constant reflecting the mass of CO_2 released per unit of lime and the average calcium plus magnesium oxide (CaO + MgO) content for lime (95 percent for both types of 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 2000). 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.

Lime emission estimates were multiplied by a factor of 1.02 to account for lime kiln dust (LKD), which is produced as a byproduct during the production of lime (IPCC 2006).

Lime emission estimates were further adjusted to account for PCC producers and sugar refineries that 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 from USGS were multiplied by a CO_2 recovery factor to determine the total amount of CO_2 recovered from lime production facilities. According to industry surveys, sugar refineries use captured CO_2 for 100 percent of their CO_2 input (Lutter 2009). Carbon dioxide recovery by PCC producers was determined by multiplying estimates for the percentage CO_2 of production weight for PCC production at lime plants by a CO_2 recovery factor based on the amount of purchased CO_2 by PCC manufacturers (Prillaman 2008 through 2010). 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).

Lime production data (high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2010 (see Table 4-8) were obtained from USGS (1992 through 2011). Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not produced in the United States (USGS 2010). 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 2000). 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) was 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 (Gg)

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
2006	15,000	2,950	2,370	409	200
2007	14,700	2,700	2,240	352	200
2008	14,900	2,310	2,070	358	200
2009	11,800	1,830	1,690	261	200
2010	13,800	2,110	1,910	239	200

Table 4-9: Adjusted Lime Production[a] (Gg)

Year	High-Calcium	Dolomitic
1990	12,514	2,809
2005	15,781	3,535
2006	16,794	3,448
2007	16,396	3,156
2008	16,467	2,771
2009	13,079	2,220
2010	15,246	2,484

[a] 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 these products and recovery rates for sugar refineries and PCC manufacturers located at lime plants. 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. 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. A detailed accounting of lime use in the United States and further research into 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.[119]

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[120]

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[119] 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).

[120] 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

The lime generated by these processes is not 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 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 Chapter 7).

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.

Uncertainties also remain surrounding recovery rates used for sugar refining and PCC production. The recovery rate for sugar refineries is based on two sugar beet processing and refining facilities located in California that use 100 percent recovered CO_2 from lime plants (Lutter 2010). This analysis assumes that all sugar refineries located on-site at lime plants also use 100 percent recovered CO_2. The recovery rate for PCC producers located on-site at lime plants is based on the 2009 value for PCC manufactured at commercial lime plants, given by the National Lime Association (Prillaman 2010).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-10. Lime CO_2 emissions were estimated to be between 12.1 and 14.3 Tg CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 8 percent below and 9 percent above the emission estimate of 13.2 Tg CO_2 Eq.

Table 4-10: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Lime Production	CO_2	13.2	12.1	14.3	-8%	+9%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Data on lime consumption for sugar refining in 2009 was revised by USGS from 733 to 731 metric tons. This revision resulted in an increase of emissions from 11,223 to 11,225 Gg CO_2 Eq., an increase of 0.02 percent.

Planned Improvements

Future improvements to the Lime Production category involve research into the availability of lime production 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 Lime Production 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

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carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + \text{heat} \rightarrow CaO + H_2O$] and no CO_2 is released.

guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[121]

Future improvements to the lime source category will also involve continued research into CO_2 recovery associated with lime use during sugar refining and precipitate calcium carbonate (PCC) production. Currently, two sugar refining facilities in California have been identified to capture CO_2 produced in lime kilns located on the same site as the sugar refinery (Lutter 2010). Data on CO_2 production by these lime facilities is unavailable. Future work will include research to determine the number of sugar refineries that employ the carbonation technique, the percentage of these that use captured CO_2 from lime production facilities, and the amount of CO_2 recovered per unit of lime production. Future research will also aim to improve estimates of CO_2 recovered as part of the PCC production process using estimates of PCC production and CO_2 inputs rather than lime consumption by PCC facilities.

4.3. Limestone and Dolomite Use (IPCC Source Category 2A3)

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[122] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass production, and environmental pollution control. 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 U.S., and significant quantities are extracted for industrial applications. For some of these applications, limestone is heated sufficiently enough to calcine the material and generate CO_2 as a byproduct. 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.

In 2010, 21,004 thousand metric tons of limestone and 2,624 thousand metric tons of dolomite were consumed for these emissive applications (USGS 2011a). Usage of limestone and dolomite resulted in aggregate CO_2 emissions of 10.0 Tg CO_2 Eq. (10,017 Gg) (see Table 4-11and Table 4-12). Overall, emissions have increased 95 percent from 1990 through 2010.

Table 4-11: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Year	Flux Stone	Glass Making	FGD	Magnesium Production	Other Miscellaneous Uses	Total
1990	2.6	0.2	1.4	0.1	0.8	5.1
2000	2.1	0.4	1.8	0.1	0.7	5.1
2005	2.7	0.4	3.0	+	0.7	6.8
2006	4.5	0.7	2.1	+	0.7	8.0
2007	2.0	0.3	3.2	+	2.2	7.7
2008	1.0	0.4	3.8	+	1.1	6.3
2009	1.8	0.1	5.4	+	0.4	7.6
2010	1.6	0.4	7.1	+	0.9	10.0

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 0.1 Tg CO2 Eq.

Table 4-12: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Year	Flux Stone	Glass Making	FGD	Magnesium Production	Other Miscellaneous Uses	Total
1990	2,593	217	1,433	64	819	5,127
2000	2,104	371	1,787	73	722	5,056
2005	2,650	425	2,975	+	718	6,768

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

[122] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

2006	4,492	747	2,061	+	735	8,035
2007	1,959	333	3,179	+	2,231	7,702
2008	974	387	3,801	+	1,114	6,276
2009	1,785	61	5,406	+	396	7,649
2010	1,572	440	7,068	+	938	10,017

+ Emissions are less than 0.1 Tg CO2 Eq.

Methodology

CO_2 emissions were calculated based on the IPCC Tier 2 method by multiplying the quantity of limestone or dolomite consumed by the average C content, 12.0 percent for limestone and 13.0 percent for dolomite (based on stoichiometry), and converting this value to CO_2. This methodology was used for flux stone, glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining and then converting to CO_2 using a molecular weight ratio. Flux stone used during the production of iron and steel was deducted from the Limestone and Dolomite Use estimate and attributed to the Iron and Steel Production estimate.

Traditionally, the production of magnesium metal was the only other significant use of limestone and dolomite that produced CO_2 emissions. At the start of 2001, there were two magnesium production plants operating in the United States and they used different production methods. One plant produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions, while the other plant produced magnesium from magnesium chloride using a CO_2-emissions-free process called electrolytic reduction. However, the plant utilizing the dolomitic process ceased its operations prior to the end of 2001, so beginning in 2002 there were no emissions from this particular sub-use (USGS 2011b).

Consumption data for 1990 through 2010 of limestone and dolomite used for flux stone, glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining (see Table 4-13) were obtained from the USGS *Minerals Yearbook: Crushed Stone Annual Report* (1995 through 2011a) and the U.S. Bureau of Mines (1991 & 1993a). The production capacity data for 1990 through 2010 of dolomitic magnesium metal also came from the USGS (1995 through 2011b) 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 uses fraction of total consumption in that year.[123]

Table 4-13: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Flux Stone	6,737	6,283	7,022	11,030	5,305	3,253	4,623	4,441
Limestone	5,804	4,151	3,165	5,208	3,477	1,970	1,631	1,921
Dolomite	933	2,132	3,857	5,822	1,827	1,283	2,992	2,520
Glass Making	489	843	962	1,693	757	879	139	1,000

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[123] This approach was recommended by USGS.

Limestone	430	843	920	1,629	757	879	139	1,000
Dolomite	59	0	43	64	0	0	0	0
FGD	3,258	4,061	6,761	4,683	7,225	8,639	12,288	16,064
Other Miscellaneous Uses	1,835	1,640	1,632	1,671	5,057	2,531	898	2,122
Total	**12,319**	**12,826**	**16,377**	**19,078**	**18,344**	**15,302**	**17,948**	**23,628**

Notes: "Other miscellaneous uses" includes chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining. Zero values for limestone and dolomite consumption for glass making result during years when the USGS reports that no limestone or dolomite are consumed for this use.

Uncertainty and Time-Series Consistency

The uncertainty levels presented in this section arise 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. Similarly, the quality of the limestone 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 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. The uncertainty of the estimates for limestone 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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-14. Limestone and Dolomite Use CO_2 emissions were estimated to be between 8.7 and 11.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 18 percent above the emission estimate of 10.0 Tg CO_2 Eq.

Table 4-14: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Limestone and Dolomite Use (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a]**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Limestone and Dolomite Use	CO_2	10.0	8.7	11.8	-13%	+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 time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Limestone and Dolomite Use category involve research into the availability of limestone and dolomite 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 Limestone and Dolomite Use 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.[124] Additionally, future improvements include revisiting the methodology to distribute withheld data across emissive end-uses for all years to improve consistency of calculations.

4.4. Soda Ash Production and Consumption (IPCC Source Category 2A4)

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. It is used primarily as an alkali, either in glass manufacturing or simply as a material that reacts with and neutralizes acids or acidic substances. 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.

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.[125] During the production process used in Wyoming, trona ore is calcined to produce crude soda ash. Carbon dixoide is generated as a byproduct of this reaction, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed.

In 2010, CO_2 emissions from the production of soda ash from trona were approximately 1.5 Tg CO_2 Eq. (1,548 Gg). Soda ash consumption in the United States generated 2.2 Tg CO_2 Eq. (2,187 Gg) in 2010. Total emissions from soda ash production and consumption in 2010 were 3.7 Tg CO_2 Eq. (3,735 Gg) (see Table 4-15 and Table 4-16). Total emissions in 2010 increased by approximately 5 percent from emissions in 2009, and have decreased overall by approximately 9.8 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. 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 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 2010 and 2011).

Table 4-15: CO_2 Emissions from Soda Ash Production and Consumption (Tg CO_2 Eq.)

Year	Production	Consumption	Total
1990	1.4	2.7	4.1
2005	1.7	2.6	4.2
2006	1.6	2.5	4.2
2007	1.7	2.5	4.1
2008	1.7	2.4	4.1
2009	1.5	2.1	3.6
2010	1.5	2.2	3.7

Note: Totals may not sum due to independent

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

[125] 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, $NaHCO_3$ was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Because the trona is 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.

rounding.

Table 4-16: CO_2 Emissions from Soda Ash Production and Consumption (Gg)

Year	Production	Consumption	Total
1990	1,431	2,710	4,141
2005	1,655	2,573	4,228
2006	1,626	2,536	4,162
2007	1,675	2,465	4,140
2008	1,733	2,366	4,099
2009	1,470	2,083	3,554
2010	1,548	2,187	3,735

Note: Totals may not sum due to independent rounding.

The United States represents about one-fourth of total world soda ash output. Based on final 2010 reported data, the estimated distribution of soda ash by end-use in 2010 was glass making, 48 percent; chemical production, 29 percent; soap and detergent manufacturing, 10 percent; distributors, 5 percent; flue gas desulfurization, 4 percent; other uses and pulp and paper production, 2 percent each; and water treatment, less than 1 percent (USGS 2011).

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. While Chinese soda ash production appears to be stabilizing, U.S. competition in Asian markets is expected to continue. Despite this competition, U.S. soda ash production is expected to increase by about 0.5 percent annually (USGS 2008).

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 following chemical reaction:

$$\underset{\text{[trona]}}{2(Na_3(CO_3)(HCO_3)\bullet 2H_2O)} \rightarrow \underset{\text{[soda ash]}}{3Na_2CO_3} + 5H_2O + CO_2$$

Based on this formula, 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 15.9 million metric tons of trona mined in 2010 for soda ash production (USGS 2011) resulted in CO_2 emissions of approximately 1.5 Tg CO_2 Eq. (1,548 Gg).

Once produced, most soda ash is consumed in glass and chemical production, with minor amounts in soap and detergents, pulp and paper, flue gas desulfurization and water treatment. As soda ash is consumed for these purposes, additional CO_2 is usually emitted. In these applications, it is assumed that one mole of C is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of C (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 4-17) between 1990 and 2010 were taken from USGS Minerals Yearbook for Soda Ash (1994 through 2011). Soda ash production and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-17: Soda Ash Production and Consumption (Gg)

Year	Production*	Consumption
1990	14,700	6,530
2005	17,000	6,200
2006	16,700	6,110
2007	17,200	5,940
2008	17,800	5,700
2009	15,100	5,020
2010	15,900	5,270

* Soda ash produced from trona ore only.

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. 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 information characterizing the emissions from each end-use is limited. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-18. Soda Ash Production and Consumption CO_2 emissions were estimated to be between 3.5and 4.0 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 3.7 Tg CO_2 Eq.

Table 4-18: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production and Consumption	CO_2	3.7	3.5	4.0	-7%	+7%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations

Trona production data was updated for 2009 and soda ash consumption data was updated for 2008 and 2009 based on newly available data from the USGS Minerals Yearbook Soda Ash 2010 (USGS 2011). This resulted in a decrease of total emissions from soda ash production and consumption for 2008 and 2009 by approximately 0.3 percent and 17 percent, respectively.

Planned Improvements

Future inventories are anticipated to estimate emissions from glass production and other use of carbonates. These inventories will extract soda ash consumed for glass production and other use of carbonates from the current soda ash consumption emission estimates and include them under those sources.

In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Soda Ash and Consumption 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.[126]

4.5. Ammonia Production (IPCC Source Category 2B1) and Urea Consumption

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-based, naphtha-based, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. One synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock; other synthetic ammonia production plants in the U.S. are using natural gas feedstock. In some plants some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. 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:

$$0.88\ CH_4 + 1.26\ \text{Air} + 1.24\ H_2O \xrightarrow{\text{(catalyst)}} 0.88\ CO_2 + N_2 + 3\ H_2$$

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$

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:

$$2\ NH_3 + CO_2 \rightarrow\ NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is attributed to 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 C 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 the Industrial Process chapter.

Total emissions of CO_2 from ammonia production in 2010 were 8.7 Tg CO_2 Eq. (8,678 Gg), and are summarized in Table 4-19 and Table 4-20. The observed decrease in ammonia production and associated CO_2 emissions between

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

2007 and 2009 is due to several factors, including market fluctuations and high natural gas prices. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, domestic producers are competing with imports from countries with lower natural gas prices (EEA 2004). The 2010 increase in ammonia production (and associated CO_2 emissions) is largely attributable to dramatically lower natural gas prices in the U.S. after 2009 (EIA 2011).

Table 4-19: CO_2 Emissions from Ammonia Production (Tg CO_2 Eq.)

Source	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Ammonia Production	13.0		9.2	8.8	9.1	7.9	7.9	8.7
Total	**13.0**		**9.2**	**8.8**	**9.1**	**7.9**	**7.9**	**8.7**

Table 4-20: CO_2 Emissions from Ammonia Production (Gg)

Source	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Ammonia Production	13,047		9,196	8,781	9,074	7,883	7,855	8,678
Total	**13,047**		**9,196**	**8,781**	**9,074**	**7,883**	**7,855**	**8,678**

Methodology

The calculation methodology for non-combustion CO_2 emissions from production of synthetic ammonia from natural gas feedstock is based on the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The method utilizes 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 (1.2 metric tons CO_2/metric ton NH_3) is applied to the percent of total annual domestic ammonia production from natural gas feedstock. Emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter.

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 stochiometric CO_2/urea factor of 44/60, assuming complete conversion of NH_3 and CO_2 to urea (IPCC 2006, EFMA 2000).

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. The CO_2 emission factor for production of ammonia from petroleum coke is based on plant specific data, wherein all C 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 for the petroleum coke feedstock process (3.57 metric tons CO_2/metric ton NH_3) 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 1995). 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. Technologies (e.g., catalytic reforming process) associated with this factor are found to closely resemble those employed in the U.S. 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. Ammonia production data (see Table 4-21) was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, and 2011) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in Current Industrial Reports Fertilizer Materials and Related Products annual and quarterly reports. Urea-ammonia nitrate production was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011). 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).

Table 4-21: Ammonia Production and Urea Production (Gg)

Year	Ammonia Production	Urea Production
1990	15,425	7,450
2005	10,143	5,270
2006	9,962	5,410
2007	10,393	5,590
2008	9,570	5,240
2009	9,372	5,084
2010	10,084	5,122

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 natural gas feedstock consumption data for the U.S. ammonia industry as a whole, 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) 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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-22. Ammonia Production CO_2 emissions were estimated to be between 7.8 and 10.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below and 25 percent above the emission estimate of 8.7 Tg CO_2 Eq.

Table 4-22: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate ($Tg CO_2 Eq.$)	Uncertainty Range Relative to Emission Estimate[a] ($Tg CO_2 Eq.$)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	8.7	7.8	10.8	-10%	+25%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, emissions resulting from non-agricultural urea consumption have been transferred from the Ammonia Production section to a new section within the Industrial Process chapter titled Urea Consumption for Non-Agricultural Purposes. This transfer decreased 1990 through 2009 emissions attributable to Ammonia Production annually by an average of 27 percent relative to the previous Inventory.

Planned Improvements

Future improvements to the Ammonia Production category involve research into the availability of ammonia production 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 Ammonia Production 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.[127] 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 used as a nitrogenous fertilizer for agricultural applications and also in a variety of industrial applications. Urea's industrial applications include its use as 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 nitrous oxide emissions from coal-fired power plants and diesel transportation motors.

Urea is produced using ammonia and CO_2 as raw materials. All urea produced in the U.S. is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. The chemical reaction that produces urea is:

$$2\,NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

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.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2010 were estimated to be 5.0 Tg CO_2 Eq. (4,978 Gg), and are summarized in Table 4-23 and Table 4-24.

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

Table 4-23: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (Tg CO_2 Eq.)

Source	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Urea Consumption	3.8		3.7	3.5	5.0	4.1	3.9	5.0
Total	**3.8**		**3.7**	**3.5**	**5.0**	**4.1**	**3.9**	**5.0**

Table 4-24: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (Gg)

Source	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Urea Consumption	3,784		3,653	3,519	4,963	4,066	3,942	4,978
Total	**3,784**		**3,653**	**3,519**	**4,963**	**4,066**	**3,942**	**4,978**

Methodology

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated by multiplying the amount of urea consumed in the U.S. 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 C in urea is released into the environment as CO_2 during use.

The amount of urea consumed for non-agricultural purposes in the U.S. 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 and is reported in Table 4-25, 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 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 stochiometric 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). Import data for urea 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 4-25). Urea export data for 1990 through 2010 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2011).

Table 4-25: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (Gg)

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
2006	5,410	4,985	5,029	656
2007	5,590	5,097	6,546	271
2008	5,240	4,925	5,459	230
2009	5,084	4,925	4,727	289
2010	5,122	4,925	6,631	152

Uncertainty and Time-Series Consistency

The amount of urea used for non-agricultural purposes is estimated based 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. There is also uncertainty associated with the assumption that all of the C in urea is released into the environment as CO_2 during use.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-26. CO_2 emissions associated with urea consumption for non-agricultural purposes were estimated to be between 2.3 and 5.0 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 48 percent below and 15 percent above the emission estimate of 4.4 Tg CO_2 Eq.

Table 4-26: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	4.4	2.3	5.0	-48%	+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 time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the urea consumption for non-agricultural purposes source category involve obtaining data on how much urea is consumed for specific applications in the United States and whether C is released to the environment fully during each application.

4.7. Nitric Acid Production (IPCC Source Category 2B2)

Nitric acid (HNO_3) is 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). During this reaction, N_2O is formed as a byproduct and is released from reactor vents into the atmosphere.

Currently, the nitric acid industry controls for emissions of NO and NO_2 (i.e., NO_x). As such, the industry in the US 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. NSCRs were widely installed in nitric plants built between 1971 and 1977. Approximately 25 percent of nitric acid plants use NSCR and they represent 15.3 percent of estimated national production (EPA 2010). The remaining 84.7 percent of production occurs using SCR or extended absorption, neither of which is known to reduce N_2O emissions.

N_2O emissions from this source were estimated to be 16.7 Tg CO_2 Eq. (54 Gg) in 2010 (see Table 4-27). Emissions from nitric acid production have decreased by 3.7 percent since 1990, with the trend in the time series closely tracking the changes in production. Emissions increased 17 percent between 2009 and 2010. Emissions have decreased by 19 percent since 1997, the highest year of production in the time series.

Table 4-27: N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	17.4	56
2005	16.2	52
2006	15.9	51
2007	18.9	61
2008	16.1	52
2009	14.3	46
2010	16.7	54

Methodology

N_2O emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. The emission factor was determined as a weighted average of two known emission factors: 2 kg N_2O/metric ton HNO_3 produced at plants using non-selective catalytic reduction (NSCR) systems and 9 kg N_2O/metric ton HNO_3 produced at plants not equipped with NSCR (IPCC 2006). In the process of destroying NO_x, NSCR systems destroy 80 to 90 percent of the N_2O, which is accounted for in the emission factor of 2 kg N_2O/metric ton HNO_3. Approximately 32 percent of HNO_3 plants in the United States are equipped with NSCR representing 17.3 percent of estimated national production (Desai 2012 and EPA 2010). Hence, the emission factor is equal to $(9 \times 0.827) + (2 \times 0.173) = 7.8$ kg N_2O per metric ton HNO_3.

Nitric acid production data for 1990 through 2002 were obtained from the U.S. Census Bureau (2010b); 2003 production data were obtained from the U.S. Census Bureau (2008); 2004 through 2007 production data were obtained from the U.S. Census Bureau (2009); 2008 and 2009 production data were obtained from the U.S. Census Bureau (2010a); and 2010 production data were obtained from the U.S. Census Bureau (2011) (see Table 4-28).

Table 4-28: Nitric Acid Production (Gg)

Year	Gg
1990	7,195
2005	6,711
2006	6,572
2007	7,827
2008	6,686
2009	5,924
2010	6,931

Uncertainty and Time-Series Consistency

The overall uncertainty associated with the 2010 N_2O emissions estimate from nitric acid production was calculated using the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of production data, the share of U.S. nitric acid production attributable to each emission abatement technology over the time series, and the emission factors applied to each abatement technology type.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-29. N_2O emissions from nitric acid production were estimated to be between 10.1 and 23.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 40 percent below to 43 percent above the 2010 emissions estimate of 16.7 Tg CO_2 Eq.

Table 4-29: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Nitric Acid Production	N_2O	16.7	10.1	23.9	-40%	+43%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Nitric Acid Production category involve research into the availability of nitric acid production 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 nitric acid production 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.[128] Specifically, the planned improvements include assessing data to update the N_2O emission factors, abatement utilization and destruction factors, and the current share of nitric acid production attributable to various abatement technologies.

Recalculations

Nitric acid production emission estimates were updated relative to the previous report. Several facilities that were previously in the Database of U.S. Nitric Acid producers were presumed to be closed in 2010 since they did not report through EPA's GHGRP in 2010 (Desai 2012). The removed facilities did not have installed NSCR systems, therefore their removal caused the weighted emissions factor equation to change. Before removal of the facilities, roughly 25 percent of nitric acid facilities had NSCR installed. After the removal, roughly 32 percent of facilities had NSCR installed, representing 17.3 percent of total U.S. production. This recalculation resulted in a 2 percent decrease in estimated N_2O emissions from Nitric Acid production in each year from 1990 through 2009, relative to the previous report.

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

4.8. Adipic Acid Production (IPCC Source Category 2B3)

Adipic acid production is an anthropogenic source of N_2O emissions. Worldwide, few adipic acid plants exist. The United States and Europe are the major producers. In 2010, the United States had two companies with a total of three adipic acid processes, two of which were operational (CW 2007; Desai 2010; VA DEQ 2009). 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. 84 percent of all adipic acid produced in the United States is used in the production of nylon 6,6; nine percent is used in the production of polyester polyols; four percent is used in the production of plasticizers; and the remaining four 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).

Adipic acid is produced through a two-stage process during which N_2O is generated in the second stage. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce 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). 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 of the three major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, the 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).

Very little information on annual trends in the activity data exist for adipic acid. Primary production data is derived from ACC *Guide to the Business of Chemistry*, which does not provide source specific trend information. The USGS does not currently publish a Minerals Yearbook for adipic acid, and it is not included in the general USGS Minerals Commodity Summary.

N_2O emissions from adipic acid production were estimated to be 2.8 Tg CO_2 Eq. (9.1 Gg) in 2010 (see Table 4-30). National adipic acid production has increased by approximately 4 percent over the period of 1990 through 2010, to roughly 760,000 metric tons. Over the same period, emissions have been reduced by 82 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 (Desai 2010).

Table 4-30: N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	15.8	51
2005	7.4	24
2006	8.9	28.7
2007	10.7	34.4
2008	2.6	8.3
2009	2.8	9.1
2010	2.8	9.1

Methodology

Due to confidential business information, plant names are not provided in this section. The four adipic acid-producing plants will henceforth be referred to as Plants 1 through 4.

For 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 (Desai 2010). These estimates were based on continuous emissions monitoring equipment installed at the two facilities. In 2009, no adipic acid production occurred at Plant 1. Due to lack of data availability, 2009 emission estimates were used as a proxy for 2010. For Plant 4, N_2O emissions were calculated by multiplying adipic acid production by an emission factor (i.e., N_2O emitted per unit of adipic acid produced) and adjusting for the percentage of N_2O released as a result of plant-specific emission controls. On the basis of experiments, the overall reaction stoichiometry for N_2O production in the preparation of adipic acid was estimated at approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). Emissions were estimated using the following equation:

$$\text{N}_2\text{O emissions} = (\text{production of adipic acid [metric tons \{MT\} of adipic acid]}) \times (0.3\ \text{MT N}_2\text{O / MT adipic acid}) \times (1 - [\text{N}_2\text{O destruction factor} \times \text{abatement system utility factor}])$$

The "N_2O destruction factor" 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. Overall, in the United States, two of the plants employ catalytic destruction (Plants 1 and 2), one plant employs thermal destruction (Plant 3), and the smallest plant used no N_2O abatement equipment (Plant 4).

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant engineer (Desai 2012). For 1990 through 2004, emissions were estimated using plant-specific production data and IPCC factors as described above for plant 4. Production data 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. 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. For Plant 4, which last operated in April 2006 (VA DEQ 2009), plant-specific production data were obtained across the time series from 1990 through 2008 (VA DEQ 2010). Since the plant has not operated since 2006, production in 2009 and 2010 are assumed to be equal to the 2008 estimate, which was zero. The plant-specific production data were then used for calculating emissions as described above.

National adipic acid production data (see Table 4-31) from 1990 through 2010 were obtained from the American Chemistry Council (ACC 2011).

Table 4-31: Adipic Acid Production (Gg)

Year	Gg
1990	735
2005	903
2006	964
2007	930
2008	869
2009	819
2010	764

Uncertainty and Time-Series Consistency

The overall uncertainty associated with the 2010 N_2O emission estimate from adipic acid production was calculated using the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) Tier 2 methodology. Uncertainty associated with N_2O emission estimates included that of the methods used by companies to monitor and estimate emissions and the use of 2009emissions data as a proxy for 2010.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-32. N_2O emissions from adipic acid production for 2010 were estimated to be between 2.6 and 3.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the 2010 emission estimate of 2.8 Tg CO_2 Eq.

Table 4-32: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	2.8	2.6	3.1	-9%	+9%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Adipic Acid Production category involve research into the availability of adipic acid production 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 Adipic Acid Production 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.[129] Specifically, the planned improvements include assessing data to update the N_2O emission factors and update abatement utility and destruction factors based on actual performance of the latest catalytic and thermal abatement equipment at plants with continuous process and emission monitoring equipment.

Recalculations

For the current Inventory, plant specific N_2O emissions data for Plant 3 were obtained directly from the plant engineer for 2005 through 2009. In the previous Inventory, 2005 through 2009 estimates of N_2O emissions from adipic acid production at Plant 3 were developed using plant production data. For Plant 3, which uses thermal destruction, the N_2O abatement system destruction factor was assumed to be 98.5 percent, and the abatement system utility factor was assumed to be 97 percent (IPCC 2006). This recalculation resulted in an 84 percent increase in average annual estimated N_2O emissions from adipic acid production between 2005 and 2009, relative to the previous report.

4.9. Silicon Carbide Production (IPCC Source Category 2B4) and Consumption

Carbon dioxide and CH_4 are emitted from the production[130] of silicon carbide (SiC), a material used as an industrial abrasive. To make SiC, quartz (SiO_2) is reacted with C in the form of petroleum coke. A portion (about 35 percent) of the C contained in the petroleum coke is retained in the SiC. The remaining C is emitted as CO_2, CH_4, or CO.

Carbon dioxide is also emitted from the consumption of SiC for metallurgical and other non-abrasive applications. The USGS reports that a portion (approximately 50 percent) of SiC is used in metallurgical and other non-abrasive

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

[130] Silicon carbide is produced for both abrasive and metallurgical applications in the United States. Production for metallurgical applications is not available and therefore both CH_4 and CO_2 estimates are based solely upon production estimates of silicon carbide for abrasive applications.

applications, primarily in iron and steel production (USGS 2006a).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. 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 2011a).

Carbon dioxide emissions from SiC production and consumption in 2010 were 0.18 Tg CO_2 Eq. (181 Gg). Approximately 51 percent of these emissions resulted from SiC production while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2010 were 0.01 Tg CO_2 Eq. CH_4 (0.4 Gg) (see Table 4-33 and Table 4-34).

Table 4-33: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq.)

Year	1990		2005	2006	2007	2008	2009	2010
CO_2	0.4		0.2	0.2	0.2	0.2	0.1	0.2
CH_4	+		+	+	+	+	+	+
Total	**0.4**		**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 4-34: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Gg)

Year	1990		2005	2006	2007	2008	2009	2010
CO_2	375		219	207	196	175	145	181
CH_4	1		+	+	+	+	+	+

+ Does not exceed 0.5 Gg.

Methodology

Emissions of CO_2 and CH_4 from the production of SiC were calculated by multiplying annual SiC production by the emission factors (2.62 metric tons CO_2/metric ton SiC for CO_2 and 11.6 kg CH_4/metric ton SiC for CH_4) provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Emissions of CO_2 from silicon carbide consumption were 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 2009). The total SiC consumed in metallurgical and other non-abrasive uses was multiplied by the C content of SiC (31.5 percent), which was determined according to the molecular weight ratio of SiC.

Production data for 1990 through 2009 were obtained from the Minerals Yearbook: Manufactured Abrasives (USGS 1991a through 2010a and 2011b). Production data for 2010 was taken from the Minerals Commodity Summary: Abrasives (Manufactured) (2011a). Silicon carbide consumption by major end use was obtained from the Minerals Yearbook: Silicon (USGS 1991b through 2010b and 2011c) (see Table 4-35) for years 1990 through 2009. Silicon carbide consumption for 2010 is proxied using 2009 data due to unavailability of data at time of publication. Net imports for the entire time series were obtained from the U.S. Census Bureau (2005 through 2011).

Table 4-35: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,465
2005	35,000	220,149

2006	35,000	199,937
2007	35,000	179,741
2008	35,000	144,928
2009	35,000	92,280
2010	35,000	154,540

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 some uncertainty associated with production, net imports, and consumption data as well as the percent of total consumption that is attributed to metallurgical and other non-abrasive uses.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-36. Silicon carbide production and consumption CO_2 emissions were estimated to be between 9 percent below and 10 percent above the emission estimate of 0.2 Tg CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.01 Tg CO_2 Eq. at the 95 percent confidence level.

Table 4-36: Tier 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Silicon Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-9%	+10%
Silicon Carbide Production	CH_4	+	+	+	-9%	+9%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.5 Gg.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Silicon Carbide Production category involve research into the availability of silicon carbide production 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 Silicon Carbide Production 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.[131] 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. Additionally, as future improvement to the silicon carbide uncertainty analysis, USGS Mineral Commodity Specialists will be contacted to verify the uncertainty range associated with silicon carbide emissive utilization.

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

4.10. Petrochemical Production (IPCC Source Category 2B5)

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. Methane emissions are presented here from the production of carbon black, ethylene, ethylene dichloride, and methanol, while CO_2 emissions are presented here for only carbon black production. The CO_2 emissions from petrochemical processes other than carbon black are currently included in the Carbon Stored in Products from Non-Energy Uses of Fossil Fuels Section of the Energy chapter. The CO_2 from carbon black production is included here to allow for the direct reporting of CO_2 emissions from the process and direct accounting of the feedstocks used in the process.

Carbon black is an intense black powder generated by the incomplete combustion of an aromatic petroleum or coal-based feedstock. 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. Ethylene 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. Ethylene dichloride is one of the first manufactured chlorinated hydrocarbons with reported production as early as 1795. In addition to being an important intermediate in the synthesis of chlorinated hydrocarbons, ethylene dichloride is used as an industrial solvent and as a fuel additive. Methanol is an alternative transportation fuel as well as a principle ingredient in windshield wiper fluid, paints, solvents, refrigerants, and disinfectants. In addition, methanol-based acetic acid is used in making PET plastics and polyester fibers.

Emissions of CO_2 and CH_4 from petrochemical production in 2010 were 3.3 Tg CO_2 Eq. (3,336 Gg) and 0.9 Tg CO_2 Eq. (44 Gg), respectively (see Table 4-37 and Table 4-38), totaling 4.3 Tg CO_2 Eq. There has been an overall increase in CO_2 emissions from carbon black production of one percent since 1990. Methane emissions from petrochemical production have increased by approximately seven percent since 1990.

Table 4-37: CO_2 and CH_4 Emissions from Petrochemical Production (Tg CO_2 Eq.)

Year	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	3.3		4.2	3.8	3.9	3.4	2.7	3.3
CH_4	0.9		1.1	1.0	1.0	0.9	0.8	0.9
Total	**4.2**		**5.3**	**4.8**	**4.9**	**4.3**	**3.6**	**4.3**

Note: Totals may not sum due to independent rounding.

Table 4-38: CO_2 and CH_4 Emissions from Petrochemical Production (Gg)

Year	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	3,311		4,181	3,837	3,931	3,449	2,735	3,336
CH_4	41		51	48	48	43	39	44

Methodology

Emissions of CH_4 were calculated by multiplying annual estimates of chemical production by the appropriate emission factor, as follows: 11 kg CH_4/metric ton carbon black, 1 kg CH_4/metric ton ethylene, 0.4 kg CH_4/metric ton ethylene dichloride,[132] and 2 kg CH_4/metric ton methanol. Although the production of other chemicals may also result in CH_4 emissions, insufficient data were available to estimate their emissions.

Emission factors were taken from the Revised 1996 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1997). Annual production data (see Table 4-39) were obtained from the American Chemistry Council's Guide to the Business of Chemistry (ACC 2002, 2003, 2005 through 2011) and the International Carbon Black Association (Johnson 2003

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[132] The emission factor obtained from IPCC/UNEP/OECD/IEA (1997), page 2.23 is assumed to have a misprint; the chemical identified should be ethylene dichloride ($C_2H_4Cl_2$) rather than dichloroethylene ($C_2H_2Cl_2$).

and 2005 through 2011). 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 through 2010 was obtained through the Methanol Institute (Jordan 2011a and 2011b).

Table 4-39: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Carbon Black	1,307		1,651	1,515	1,552	1,362	1,080	1,317
Ethylene	16,541		23,954	25,000	25,392	22,539	22,596	23,961
Ethylene Dichloride	6,282		11,260	9,736	9,566	8,981	8,131	8,820
Methanol	3,785		2,336	1,123	1,068	810	810	903

Almost all carbon black in the United States is produced from petroleum-based or coal-based feedstocks using the "furnace black" process (European IPPC Bureau 2004). The furnace black process is a partial combustion process in which a portion of the carbon black feedstock is combusted to provide energy to the process. Carbon black is also produced in the United States by the thermal cracking of acetylene-containing feedstocks ("acetylene black process") and by the thermal cracking of other hydrocarbons ("thermal black process"). One U.S carbon black plant produces carbon black using the thermal black process, and one U.S. carbon black plant produces carbon black using the acetylene black process (The Innovation Group 2004).

The furnace black process produces carbon black from "carbon black feedstock" (also referred to as "carbon black oil"), which is a heavy aromatic oil that may be derived as a byproduct of either the petroleum refining process or the metallurgical (coal) coke production process. For the production of both petroleum-derived and coal-derived carbon black, the "primary feedstock" (i.e., carbon black feedstock) is injected into a furnace that is heated by a "secondary feedstock" (generally natural gas). Both the natural gas secondary feedstock and a portion of the carbon black feedstock are oxidized to provide heat to the production process and pyrolyze the remaining Carbon black feedstock to carbon black. The "tail gas" from the furnace black process contains CO_2, carbon monoxide, sulfur compounds, CH_4, and non-CH_4 volatile organic compounds. A portion of the tail gas is generally burned for energy recovery to heat the downstream carbon black product dryers. The remaining tail gas may also be burned for energy recovery, flared, or vented uncontrolled to the atmosphere.

The calculation of the C lost during the production process is the basis for determining the amount of CO_2 released during the process. The C content of national carbon black production is subtracted from the total amount of C contained in primary and secondary carbon black feedstock to find the amount of C lost during the production process. It is assumed that the C lost in this process is emitted to the atmosphere as either CH_4 or CO_2. The C content of the CH_4 emissions, estimated as described above, is subtracted from the total C lost in the process to calculate the amount of C emitted as CO_2. The total amount of primary and secondary carbon black feedstock consumed in the process (see Table 4-40) is estimated using a primary feedstock consumption factor and a secondary feedstock consumption factor estimated from U.S. Census Bureau (1999, 2004, and 2007) data. The average carbon black feedstock consumption factor for U.S. carbon black production is 1.69 metric tons of carbon black feedstock consumed per metric ton of carbon black produced. The average natural gas consumption factor for U.S. carbon black production is 321 normal cubic meters of natural gas consumed per metric ton of carbon black produced. The amount of C contained in the primary and secondary feedstocks is calculated by applying the respective C contents of the feedstocks to the respective levels of feedstock consumption (EIA 2003, 2004).

Table 4-40: Carbon Black Feedstock (Primary Feedstock) and Natural Gas Feedstock (Secondary Feedstock) Consumption (Thousand Metric Tons)

Activity	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Primary Feedstock	2,213		2,794	2,564	2,627	2,305	1,828	2,230
Secondary Feedstock	284		359	329	337	296	235	286

For the purposes of emissions estimation, 100 percent of the primary carbon black feedstock is assumed to be derived from petroleum refining byproducts. Carbon black feedstock derived from metallurgical (coal) coke production (e.g., creosote oil) is also used for carbon black production; however, no data are available concerning the annual consumption of coal-derived carbon black feedstock. Carbon black feedstock derived from petroleum refining byproducts is assumed to be 89 percent elemental C (Srivastava et al. 1999). It is assumed that 100 percent of the tail gas produced from the carbon black production process is combusted and that none of the tail gas is vented to the atmosphere uncontrolled. The furnace black process is assumed to be the only process used for the production of carbon black because of the lack of data concerning the relatively small amount of carbon black produced using the acetylene black and thermal black processes. The carbon black produced from the furnace black process is assumed to be 97 percent elemental C (Othmer et al. 1992).

Uncertainty and Time-Series Consistency

The CH_4 emission factors used for petrochemical production are based on a limited number of studies. Using plant-specific factors instead of average factors could increase the accuracy of the emission estimates; however, such data were not available. There may also be other significant sources of CH_4 arising from petrochemical production activities that have not been included in these estimates.

The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production calculation are based on feedstock consumption, import and export data, and carbon black production data. The composition of carbon black feedstock varies depending upon the specific refinery production process, and therefore the assumption that carbon black feedstock is 89 percent C gives rise to uncertainty. Also, no data are available concerning the consumption of coal-derived carbon black feedstock, so CO_2 emissions from the utilization of coal-based feedstock are not included in the emission estimate. In addition, other data sources indicate that the amount of petroleum-based feedstock used in carbon black production may be underreported by the U.S. Census Bureau. Finally, the amount of carbon black produced from the thermal black process and acetylene black process, although estimated to be a small percentage of the total production, is not known. Therefore, there is some uncertainty associated with the assumption that all of the carbon black is produced using the furnace black process.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-41. Petrochemical production CO_2 emissions were estimated to be between 2.4 and 4.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 28 percent below to 31 percent above the emission estimate of 3.3 Tg CO_2 Eq. Petrochemical production CH_4 emissions were estimated to be between 0.7 and 1.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 29 percent below to 30 percent above the emission estimate of 0.9 Tg CO_2 Eq.

Table 4-41: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Carbon Black Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Petrochemical Production	CO_2	3.3	2.4	4.4	-28%	+31%
Petrochemical Production	CH_4	0.9	0.7	1.2	-29%	+30%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations

Methanol production data for 2008 and 2009 was updated relative to the previous report based on correspondence with Jim Jordan of Jordan Associates (Jordan 2011a and 2011b). This resulted in a decrease of total CO_2 and CH_4 emissions from petrochemical production of less than 1 percent.

Planned Improvements

Future improvements to the petrochemicals source category involve updating the methodology to use CH_4 emission factors for petrochemical production from the IPCC 2006 guidelines rather than the IPCC 1996 guidelines. Further future improvements to the Petrochemical Production category involve research into the availability of petrochemical production 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 Petrochemical Production 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.[133] In addition, the planned improvements include assessing the data EPA obtains to update data sources for acrylonitrile production in the United States.

4.11. Titanium Dioxide Production (IPCC Source Category 2B5)

Titanium dioxide (TiO_2) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. Titanium dioxide is a principal ingredient in white paint, and is also used as a pigment in the manufacture of white paper, foods, and other products. There are two processes for making TiO_2: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related CO_2. The sulfate process does not use petroleum coke or other forms of C as a raw material and does not emit CO_2.

The chloride process is based on the following chemical reactions:

$$2\ FeTiO_3 + 7\ Cl_2 + 3\ C \rightarrow 2\ TiCl_4 + 2\ FeCl_3 + 3\ CO_2$$

$$2\ TiCl_4 + 2\ O_2 \rightarrow 2\ TiO_2 + 4\ Cl_2$$

The C in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (the Ti-containing ore) to form CO_2. The majority of U.S. TiO_2 was produced in the United States through the chloride process, and a special grade of "calcined" petroleum coke is manufactured specifically for this purpose.

Emissions of CO_2 in 2010 were 1.9 Tg CO_2 Eq. (1,876 Gg), which represents an increase of 57 percent since 1990 (see Table 4-42).

Table 4-42: CO_2 Emissions from Titanium Dioxide (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.2	1,195
2005	1.8	1,755
2006	1.8	1,836
2007	1.9	1,930
2008	1.8	1,809
2009	1.6	1,648
2010	1.9	1,876

Methodology

Emissions of CO_2 from TiO_2 production were calculated by multiplying annual TiO_2 production by chloride-process-specific emission factors.

Data were obtained for the total amount of TiO_2 produced each year. For years previous 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

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

U.S. production capacity for each process. As of 2004, the last remaining sulfate-process plant in the United States had closed; therefore, 100 percent of post-2004 production uses the chloride process (USGS 2005). An emission factor of 0.4 metric tons C/metric ton TiO_2 was applied to the estimated chloride-process production. 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 C inputs. The amount of petroleum coke consumed annually in TiO_2 production was calculated based on the assumption that the calcined petroleum coke used in the process is 98.4 percent C and 1.6 percent inert materials (Nelson 1969).

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2009 (see Table 4-43) were obtained through the Minerals Yearbook: Titanium Annual Report (USGS 1991 through 2011b). Production data for 2010 was obtained from the Minerals Commodity Summary: Titanium and Titanium Dioxide (USGS 2011a). Due to lack of available 2010 capacity data at the time of publication, the 2009 capacity estimate is used as a proxy for 2010. Percentage chloride-process data 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 4-43: Titanium Dioxide Production (Gg)

Year	Gg
1990	979
2005	1,310
2006	1,370
2007	1,440
2008	1,350
2009	1,230
2010	1,400

Uncertainty and Time-Series Consistency

Although some TiO_2 may be produced using graphite or other C 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.

Also, annual TiO_2 is not reported by USGS by the type of production process used (chloride or sulfate). Only the percentage of total production capacity by process is 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 (since, as of 2004, the last remaining sulfate-process plant in the United States closed). This assumes that the chloride-process plants and sulfate-process plants operate at the same level of utilization. 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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-44. Titanium dioxide consumption CO_2 emissions were estimated to be between 1.6 and 2.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.9 Tg CO_2 Eq.

Table 4-44: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.9	1.6	2.1	-12%	+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 time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations

Production data for 2009 were updated relative to the previous Inventory based on recently published data in the USGS Minerals Yearbook: Titanium 2009 (USGS 2011). This resulted in a 7 percent decrease in 2009 CO_2 emissions from TiO_2 production relative to the previous report.

Planned Improvements

Future improvements to the Titanium Dioxide Production category involve research into the availability of titanium dioxide production 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 Titanium Dioxide Production 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.[134] 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.

4.12. Carbon Dioxide Consumption (IPCC Source Category 2B5)

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

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

are therefore accounted for under Ammonia Production, Fossil Fuel Combustion, or other appropriate source category.[135]

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 and two in New Mexico) 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 is producing CO_2 from naturally occurring CO_2 reservoirs for commercial applications only. 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 2010, the amount of CO_2 produced by the Colorado, Mississippi, and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere was 2.2 Tg CO_2 Eq. (2,202 Gg) (see Table 4-45). This is an increase of 23 percent from the previous year and an increase of 56 percent since 1990. This increase was largely due to an in increase in production at the Mississippi facility, despite the low percentage (13 percent) of the facility's total reported production that was used for commercial applications in 2010.

Table 4-45: CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.4	1,416
2005	1.3	1,321
2006	1.7	1,709
2007	1.9	1,867
2008	1.8	1,780
2009	1.8	1,784
2010	2.2	2,203

Methodology

CO_2 emission estimates for 1990 through 2010 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 for the Jackson Dome, Mississippi facility and the percentage of production that was used for non-EOR applications were obtained from Advanced Resources International (ARI 2006, 2007) for 1990 to 2000 and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2011) for 2001 to 2010 (see Table 4-46). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2010 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 2000 was set equal to 2001 production. Carbon dioxide production data for the Bravo Dome, New Mexico facilities were obtained from ARI (ARI 1990 through 2011). Data for the West Bravo Dome facility was only available for 2009 and 2010. The percentage of total production that was used for non-EOR applications were

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[135] There are currently four known electric power plants operating in the U.S. 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.

obtained from the 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, Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2010 (COGCC 2011). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999.

Table 4-46: CO_2 Production (Gg CO_2) and the Percent Used for Non-EOR Applications

Year	**Jackson Dome CO_2 Production (Gg) (% Non-EOR)**	**Bravo Dome CO_2 Production (Gg) (% Non-EOR)**	**West Bravo Dome CO_2 Production (Gg) (% Non-EOR)**	**McCallum Dome CO_2 Production (Gg) (% Non-EOR)**
1990	1,353 (100%)	6,301 (1%)	-	0.07 (100%)
2005	4,677 (27%)	5,798 (1%)	-	0.06(100%)
2006	6,610 (25%)	5,605 (1%)	-	0.06(100%)
2007	9,529 (19%)	5,605 (1%)	-	0.07(100%)
2008	12,312 (14%)	5,605 (1%)	-	0.07(100%)
2009	13,201 (13%)	4,639 (1%)	2,126 (1%)	0.02(100%)
2010	16,487 (13%)	4,832 (1%)	870 (1%)	0.05(100%)

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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-47. Carbon dioxide consumption CO_2 emissions were estimated to be between 1.6 and 2.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 26 percent below to 30 percent above the emission estimate of 2.2 Tg CO_2 Eq.

Table 4-47: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
CO_2 Consumption	CO_2	2.2	1.6	2.9	-26%	+30%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, two new facilities, the West Bravo and McCallum domes, were added to the time series. The impact of these facilities upon emission estimates for the time series, relative to the previous report, is negligible.

Planned Improvements

Future improvements to the Carbon Dioxide Consumption category involve research into the availability of carbon dioxide consumption data, and analyzing data reported to EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Carbon Dioxide Consumption 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.[136]

4.13. Phosphoric Acid Production (IPCC Source Category 2B5)

Phosphoric acid (H_3PO_4) is a basic raw material in the production of phosphate-based fertilizers. 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 production of phosphoric acid from phosphate rock produces byproduct gypsum ($CaSO_4$-$2H_2O$), referred to as phosphogypsum.

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 C in the form of calcium carbonate (limestone) and also may contain organic C. The chemical composition of phosphate rock (francolite) mined in Florida is:

$$Ca_{10-x-y}\,Na_x\,Mg_y\,(PO_4)_{6-x}(CO_3)_xF_{2+0.4x}$$

The calcium carbonate component of the phosphate rock is integral to the phosphate rock chemistry. Phosphate rock can also contain organic C that is physically incorporated into the mined rock but is not an integral component of the phosphate rock chemistry. Phosphoric acid production from natural phosphate rock is a source of CO_2 emissions, due to the chemical reaction of the inorganic C (calcium carbonate) component of the phosphate rock.

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). The primary chemical reactions for the production of phosphoric acid from phosphate rock are:

$$Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$$

$$3Ca(H_2PO_4)_2 + 3H_2SO_4 + 6H_2O \rightarrow 3CaSO_4 \bullet 6H_2O + 6H_3PO_4$$

The limestone ($CaCO_3$) component of the phosphate rock reacts with the sulfuric acid in the phosphoric acid production process to produce calcium sulfate (phosphogypsum) and CO_2. The chemical reaction for the limestone-sulfuric acid reaction is:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \bullet 2H_2O + CO_2$$

Total marketable phosphate rock production in 2010 was 25.8 million metric tons (USGS 2011). Approximately 87 percent of domestic phosphate rock production was mined in Florida and North Carolina, while approximately 13 percent of production was mined in Idaho and Utah. Total imports of phosphate rock in 2010 were 2.4 million metric tons (USGS 2011). The vast majority, 99 percent, of imported phosphate rock is sourced from Morocco (USGS 2005). Marketable phosphate rock production, including domestic production and imports for consumption stayed relatively flat between 2009 and 2010, decreasing by 2.3 percent between 2009 and 2010. Over the 1990 to 2010 period, domestic production has decreased by nearly 48 percent. Total CO_2 emissions from phosphoric acid production were 1.0 Tg CO_2 Eq. (1,017 Gg) in 2010 (see Table 4-48). After experiencing weak market conditions due to the global economic downturn in 2008 and 2009, demand for and trade in phosphate rock increased in 2010 (USGS 2011).

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

Table 4-48: CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.5	1,529
2005	1.4	1,386
2006	1.2	1,167
2007	1.2	1,166
2008	1.2	1,187
2009	1.0	1,018
2010	1.0	1,017

Methodology

CO_2 emissions from production of phosphoric acid from phosphate rock are calculated by multiplying the average amount of calcium carbonate contained in the natural phosphate rock by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption.

The CO_2 emissions calculation methodology is based on the assumption that all of the inorganic C (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 C content of the phosphate rock is converted to CO_2 and that all of the organic C 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 4-49). For the years 1990, 1991, 1992, and 2005 through 2010, only nationally aggregated mining data was reported by USGS. For these years, 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. Data for domestic production of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption for 1990 through 2010 were obtained from *USGS Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2011). From 2004 through 2010, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005 through 2011).

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 C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-50).

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 (87 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). Carbonate content data for uncalcined phosphate rock mined in Idaho and Utah (13 percent of domestic production) were not available, and carbonate content was therefore estimated from the carbonate content data for calcined phosphate rock mined in Idaho.

Table 4-49: Phosphate Rock Domestic Production, Exports, and Imports (Gg)

Location/Year	1990		2005	2006	2007	2008	2009	2010
U.S. Production[a]	49,800		36,100	30,100	29,700	30,200	26,400	25,800
FL & NC	42,494		31,227	26,037	25,691	26,123	22,836	22,317
ID & UT	7,306		4,874	4,064	4,010	4,077	3,564	3,483

Exports—FL & NC	6,240		-	-	-	-	-	-
Imports—Morocco	451		2,630	2,420	2,670	2,750	2,000	2,400
Total U.S. Consumption	**44,011**		**38,730**	**32,520**	**32,370**	**32,950**	**28,400**	**28,200**

[a] USGS does not disaggregate production data regionally (FL & NC and ID & UT) for 1990 and 2005 through 2010. Data for those years are estimated based on the remaining time series distribution.

- Assumed equal to zero.

Table 4-50: 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	-	0.10
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00

Source: FIPR 2003

- Assumed equal to zero.

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 2010. For previous years in the time series, USGS provided the data disaggregated regionally; however, beginning in 2006 only total U.S. phosphate rock production were reported. Regional production for 2010 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 2010 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. Another source of uncertainty is the disposition of the organic C 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 C 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 the USGS, only one producer in Idaho is currently calcining phosphate rock, and no data were available concerning the annual production of this single producer (USGS 2005). For available years, total production of phosphate rock in Utah and Idaho combined amounts to approximately 13 percent of total domestic production on average (USGS 1994 through 2005).

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 C content in phosphate rock, but none from the organic C content.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-51. Phosphoric acid production CO_2 emissions were estimated to be between 0.8 and 1.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 18 percent above the emission estimate of 1.0 Tg CO_2 Eq.

Table 4-51: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Phosphoric Acid Production	CO_2	1.0	0.8	1.2	-18%	+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 time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations

Phosphate rock import and production values for 2008 and 2009 were updated relative to the previous Inventory based on recently published data (USGS 2011). This resulted in a decrease in 2008 and 2009 emissions by less than 1 percent and approximately 2 percent, respectively, relative to the previous report.

Planned Improvements

Future improvements to the Phosphoric Acid Production category involve research into the availability of phosphoric acid production data, and analyzing data reported to EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Phosphoric Acid Production 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.[137] Additionally, as a future improvement to the phosphoric acid uncertainty analysis, USGS Mineral Commodity Specialists will be contacted to verify uncertainty ranges associated with phosphate rock imports and exports.

4.14. Iron and Steel Production (IPCC Source Category 2C1) and Metallurgical Coke Production

The production of iron and steel is an energy-intensive activity that also generates process-related emissions of CO_2 and CH_4. Process emissions occur at each step of steel production from the production of raw materials to the refinement of iron to the making of crude steel. In the United States, steel is produced through both primary and secondary processes. Historically, primary production—using a basic oxygen furnace (BOF) with pig iron as the primary feedstock—has been the dominant method. But secondary production through the use scrap steel and electric arc furnaces (EAFs) has increased significantly in recent years due to the economic advantages of steel recycling, which has been driven by the increased availability of scrap steel. Total production of crude steel in the United States in the time period between 2000 and 2008 ranged from a low of 99,320,000 tons to a high of 109,879,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn, especially from the automotive industry, crude steel production in the United States decreased to 65,460,000 tons in 2009. In 2010, crude steel production rebounded to 88,730,000 tons as economic conditions improved (AISI 2011a).

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

Metallurgical coke is an important input in the production of iron and steel. Coke is used to produce iron or pig iron feedstock from raw iron ore. The production of metallurgical coke from coking coal occurs both on-site at "integrated" iron and steel plants and off-site at "merchant" coke plants. Metallurgical coke is produced by heating coking coal in a coke oven in a low-oxygen environment. The process drives off the volatile components of the coking coal and produces coal (metallurgical) coke. Carbon containing byproducts of the metallurgical coke manufacturing process include coke oven gas, coal tar, coke breeze (small-grade coke oven coke with particle size <5mm) and light oil. Coke oven gas is recovered and used for underfiring the coke ovens and within the iron and steel mill. Small amounts of coke oven gas are also sold as synthetic natural gas outside of iron and steel mills (and are accounted for in the Energy chapter). Coal tar is used as a raw material to produce anodes used for primary aluminum production, electric arc furnace (EAF) steel production, and other electrolytic processes, and also is used in the production of other coal tar products. Light oil is sold to petroleum refiners who use the material as an additive for gasoline. The metallurgical coke production process produces CO_2 emissions and fugitive CH_4 emissions.

Iron is produced by first reducing iron oxide (iron ore) with metallurgical coke in a blast furnace. Iron can be introduced into the blast furnace in the form of raw iron ore, taconite pellets (9-16mm iron-containing spheres), briquettes, or sinter. In addition to metallurgical coke and iron, other inputs to the blast furnace include natural gas, fuel oil, and coke oven gas. The carbon in the metallurgical coke used in the blast furnace combines with oxides in the iron ore in a reducing atmosphere to produce blast furnace gas containing carbon monoxide (CO) and CO_2. The CO is then converted and emitted as CO_2 when combusted to either pre-heat the blast air used in the blast furnace or for other purposes at the steel mill. This pig iron or crude iron that is produced from this process contains about 3 to 5 percent carbon by weight. The pig iron production process in a blast furnace produces CO_2 emissions and fugitive CH_4 emissions.

Iron can also be produced through the direct reduction process; wherein, iron ore is reduced to metallic iron in the solid state at process temperatures less than 1000°C. Direct reduced iron production results in process emissions of CO_2 and emissions of CH_4 through the consumption of natural gas used during the reduction process.

Sintering is a thermal process by which fine iron-bearing particles, such as air emission control system dust, are baked, which causes the material to agglomerate into roughly one-inch pellets that are then recharged into the blast furnace for pig iron production. Iron ore particles may also be formed into larger pellets or briquettes by mechanical means, and then agglomerated by heating. The agglomerate is then crushed and screened to produce an iron-bearing feed that is charged into the blast furnace. The sintering process produces CO_2 and fugitive CH_4 emissions through the consumption of carbonaceous inputs (e.g., coke breeze) during the sintering process.

Steel is produced from varying levels of pig iron and scrap steel in specialized BOF and EAF steel-making furnaces. Carbon inputs to BOF steel-making furnaces include pig iron and scrap steel as well as natural gas, fuel oil, and fluxes (e.g., limestone, dolomite). In a BOF, the carbon in iron and scrap steel combines with high-purity oxygen to reduce the carbon content of the metal to the amount desired for the specified grade of steel. EAFs use carbon electrodes, charge carbon and other materials (e.g., natural gas) to aid in melting metal inputs (primarily recycled scrap steel), which are refined and alloyed to produce the desired grade of steel. Carbon dioxide emissions occur in BOFs through the reduction process. In EAFs, CO_2 emissions result primarily from the consumption of carbon electrodes and also from the consumption of supplemental materials used to augment the melting process.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold for use as synthetic natural gas are deducted and reported in the Energy chapter (emissions associated with natural gas and fuel oil consumption for these purposes are reported in the Energy chapter).

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts at the iron and steel mill, with lesser amounts emitted from the use of flux and from the removal of carbon from pig iron used to produce steel. Some carbon is also stored in the finished iron and steel products.

According to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (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 Guidelines suggest that emissions from the production of metallurgical coke should be reported separately in the Energy source, while emissions from coke consumption in iron and steel production should be reported in the industrial process source. 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. Further, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed to point of consumption. As an example, CO_2 emissions associated with the combustion of coke oven gas in the blast furnace during pig iron production are attributed to pig iron production. Emissions associated with the use of conventional fuels (e.g., natural gas and fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 and CH_4 from metallurgical coke production in 2010 were 2.1 Tg CO_2 Eq. (2,084 Gg) and less than 0.00003 Tg CO_2 Eq. (less than 0.002 Gg), respectively (see Table 4-52 and Table 4-53), totaling 2.1 Tg CO_2 Eq. Emissions increased in 2010 yet have decreased overall since 1990. In 2010, domestic coke production increased by 35 percent but has decreased overall since 1990. Coke production in 2010 was 28 percent lower than in 2000 and 46 percent below 1990. Overall, emissions from metallurgical coke production have declined by 16 percent (0.4 Tg CO_2 Eq.) from 1990 to 2010.

Table 4-52: CO_2 and CH_4 Emissions from Metallurgical Coke Production (Tg CO_2 Eq.)

Year	1990		2005	2006	2007	2008	2009	2010
CO_2	2.5		2.0	1.9	2.1	2.3	1.0	2.1
CH_4	+		+	+	+	+	+	+
Total	**2.5**		**2.0**	**1.9**	**2.1**	**2.3**	**1.0**	**2.1**

+ Does not exceed 0.05 Tg CO_2 Eq.

Table 4-53: CO_2 and CH_4 Emissions from Metallurgical Coke Production (Gg)

Year	1990		2005	2006	2007	2008	2009	2010
CO_2	2,470		2,043	1,919	2,055	2,334	956	2,084
CH_4	+		+	+	+	+	+	+

+ Does not exceed 0.5 Gg

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2010 were 52.2 Tg CO_2 Eq. (52,192 Gg) and 0.5 Tg CO_2 Eq. (24.5 Gg), respectively (see Table 4-54 through Table 4-57), totaling approximately 52.7 Tg CO_2 Eq. Emissions increased in 2010—largely due to increased steel production associated with improved economic conditions—but 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 2010, domestic production of pig iron increased by 41 percent from 2009 levels. Overall, domestic pig iron production has declined since the 1990s. Pig iron production in 2010 was 44 percent lower than in 2000 and 46 percent below 1990. Carbon dioxide emissions from steel production have increased by 5 percent (0.4 Tg CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 46 percent (44.9 Tg CO_2 Eq.) from 1990 to 2010.

Table 4-54: CO_2 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Year	1990	2005	2006	2007	2008	2009	2010
Sinter Production	2.4	1.7	1.4	1.4	1.3	0.8	1.0
Iron Production	47.9	19.6	24.0	27.3	25.8	16.0	19.0
Steel Production	7.5	8.5	8.9	9.4	7.5	6.6	7.8
Other Activities[a]	39.3	34.2	32.6	31.0	29.1	17.8	24.3
Total	**97.1**	**64.0**	**66.9**	**69.1**	**63.8**	**41.2**	**52.2**

Note: Totals may not sum due to independent rounding.

[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.

Table 4-55: CO_2 Emissions from Iron and Steel Production (Gg)

Year	1990	2005	2006	2007	2008	2009	2010
Sinter Production	2,448	1,663	1,418	1,383	1,299	763	1,045
Iron Production	47,944	19,645	24,010	27,353	25,773	15,995	19,042
Steel Production	7,476	8,489	8,924	9,384	7,540	6,585	7,844
Other Activities[a]	39,256	34,160	32,583	30,964	29,146	17,815	24,260
Total	**97,123**	**63,957**	**66,934**	**69,083**	**63,758**	**41,157**	**52,192**

Note: Totals may not sum due to independent rounding.

[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.

Table 4-56: CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Year	1990	2005	2006	2007	2008	2009	2010
Sinter Production	+	+	+	+	+	+	+
Iron Production	0.9	0.7	0.7	0.7	0.6	0.4	0.5
Total	**1.0**	**0.7**	**0.7**	**0.7**	**0.6**	**0.4**	**0.5**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-57: CH_4 Emissions from Iron and Steel Production (Gg)

Year	1990	2005	2006	2007	2008	2009	2010
Sinter Production	0.9	0.6	0.5	0.5	0.4	0.3	0.4
Iron Production	44.7	33.5	34.1	32.7	30.4	17.1	24.2
Total	**45.6**	**34.1**	**34.6**	**33.2**	**30.8**	**17.4**	**24.5**

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates presented in this chapter are largely based on Tier 2 methodologies provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (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 (e.g. DRI production) for which available data are insufficient for utilizing a Tier 2 method.

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 lead and zinc (see Lead

Production and Zinc Production in 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 for National Greenhouse Gas Inventories* (IPCC 2006) was utilized. The amount of carbon 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, 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 carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-58). 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. 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 4-58: 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 (0.1 g CH_4 per metric ton) taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (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 2011d) (see Table 4-59). 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 2011a) and through personal communications with AISI (2008b) (see Table 4-60). The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (2008b). 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 for National Greenhouse Gas Inventories* (IPCC 2006). The C content for coke breeze was assumed to equal the C content of coke.

Table 4-59: 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**	**2006**	**2007**	**2008**	**2009**	**2010**
Metallurgical Coke Production								

Coking Coal Consumption at Coke Plants	35,269	21,259	20,827	20,607	20,022	13,904	19,135
Coke Production at Coke Plants	25,054	15,167	14,882	14,698	14,194	10,109	13,628
Coal Breeze Production	2,645	1,594	1,562	1,546	1,502	1,043	1,435
Coal Tar Production	1,058	638	625	618	601	417	574

Table 4-60: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (million ft^3)

Source/Activity Data	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Metallurgical Coke Production							
Coke Oven Gas Production[a]	250,767	114,213	114,386	109,912	103,191	66,155	95,405
Natural Gas Consumption	599	2,996	3,277	3,309	3,134	2,121	3,108
Blast Furnace Gas Consumption	24,602	4,460	5,505	5,144	4,829	2,435	3,181

[a] Includes coke oven gas used for purposes other than coke oven underfiring only.

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 4-61). Because estimates of sinter production and direct reduced iron production were not available, production was assumed to equal consumption.

Table 4-61: 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, 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 4-62). 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 carbon 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 carbon contained in inputs such as natural gas, coke oven gas, fluxes, and pig iron. In each case, the C was calculated by multiplying material-specific carbon contents by each material type (see Table 4-62). 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 2008b)). The amount of flux (e.g., limestone and dolomite) used during steel manufacture was deducted from the Limestone and Dolomite Use 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 C content (see Table 4-62).

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 4-54and Table 4-55).

Table 4-62: 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 for National Greenhouse Gas Inventories* (IPCC 2006) for sinter production and the 1995 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1995) (see Table 4-63) 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 emissions estimates are excluded due to data limitations.

Table 4-63: 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 and direct reduced iron consumption data were obtained from AISI's Annual Statistical Report (AISI 2004 through 2011a) and through personal communications with AISI (2008b) (see Table 4-64). Data on direct reduced iron consumed in EAFs were not available for the years 1990, 1991, 1999, 2006, 2007, 2008, 2009, and 2010. EAF direct reduced iron consumption in 1990 and 1991 were assumed to equal consumption in 1992, and consumption in 1999 was assumed to equal the average of 1998 and 2000. EAF consumption in 2006, 2007, 2008,2009, and 2010 were calculated by multiplying the total DRI consumption for all furnaces as provided in the 2010 AISI Annual Statistical Report by the EAF share of total DRI consumption in 2005 (the most recent year that data was available for EAF vs. BOF consumption of DRI). Data on direct reduced iron consumed in BOFs were not available for the years 1990 through 1994, 1999, 2006, 2007, 2008, 2009, and 2010. BOF direct reduced iron consumption in 1990 through 1994 was assumed to equal consumption in 1995, and consumption in 1999 was assumed to equal the average of 1998 and 2000. BOF consumption in 2006, 2007, 2008, 2009, and 2010 were calculated by multiplying the total DRI consumption for all furnaces as provided in the USGS Mineral Industry Survey: Iron and Steel Scrap in December 2010 (USGS 2011) by the BOF share of total DRI consumption in 2005 (the most recent year that data was available from the AISI Annual Statistical Reports for EAF vs. BOF consumption of DRI).[138] The Tier 1 CO_2 emission factors for sinter production and direct reduced iron production were obtained through the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). Data for

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[138] 2010 DRI consumption values were not yet available when the 2010 AISI Annual Statistical Report was published, so the USGS Minerals Survey was used as a proxy.

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 2011a) and through personal communications with AISI (2008b) (see Table 4-65). Data for EAF steel production, flux, EAF charge carbon, direct reduced iron, pig iron, scrap steel, and natural gas consumption were obtained from AISI's Annual Statistical Report (AISI 2004 through 2011a) and through personal communications with AISI (2011b and 2008b). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (AISI 2008b). Data for BOF steel production, flux, direct reduced iron, pig iron, scrap steel, natural gas, natural ore, pellet sinter consumption as well as BOF steel production were obtained from AISI's Annual Statistical Report (AISI 2004 through 2011a) and through personal communications with AISI (2008b). Because data on pig iron consumption in BOFs and EAFs were not available for 2006, 2007, and 2008 while scrap steel consumption data in BOFs and EAFs were not available for 2006 and 2007, values for these years were calculated by multiplying the total pig iron and scrap steel consumption for all furnaces as provided in the USGS Minerals Survey: Iron and Steel Scrap in December 2010 (USGS 2011) by the BOF and EAF shares of total pig iron and scrap consumption in 2005 (the most recent year that data was available from the AISI Annual Statistical Reports for EAF vs. BOF consumption of pig iron and scrap steel).[139] Because data for pig iron consumption in EAFs was also not available in 2003 and 2004, the average of 2002 and 2005 pig iron consumption data were used. 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 2011a) and through personal communications with AISI (2008b). Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's Natural Gas Annual 2010 (EIA 2011b). C contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The C contents for natural gas, fuel oil, and direct injection coal were obtained from EIA 2011c and EPA 2010. Heat contents for the same fuels were obtained from EIA (1992, 2011a). 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 4-64: 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	2006	2007	2008	2009	2010
Sinter Production							
Sinter Production	12,239	8,315	7,088	6,914	6,497	3,814	5,225
Direct Reduced Iron Production							
Direct Reduced Iron Production	936	1,633	1,497	2,087	1,769	1,243	1,343
Pig Iron Production							
Coke Consumption	24,946	13,832	14,684	15,039	14,251	8,572	10,883
Pig Iron Production	49,669	37,222	37,904	36,337	33,730	19,019	26,844
Direct Injection Coal Consumption	1,485	2,573	2,526	2,734	2,578	1,674	2,279
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,245	1,214	1,109	845	1,189
Scrap Steel Consumption	35,743	37,558	38,033	40,845	40,824	35,472	36,560
Flux Consumption	319	695	671	567	680	476	640
EAF Steel Production	33,511	52,194	56,071	57,004	52,791	36,725	49,339
BOF Steel Production							
Pig Iron Consumption	46,564	32,115	32,638	33,773	29,322	24,404	28,214
Scrap Steel Consumption	14,548	11,612	11,759	12,628	8,029	6,641	8,881
Flux Consumption	576	582	610	408	431	318	408
BOF Steel Production	43,973	42,705	42,119	41,099	39,105	22,659	31,158

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[139] 2010 pig iron and scrap steel consumption values were not yet available when the 2010 AISI Annual Statistical Report was published, so the USGS Minerals Survey was used as a proxy.

Table 4-65: 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	2006	2007	2008	2009	2010
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	58,344	56,112	53,349	35,933	47,814
Fuel Oil Consumption (thousand gallons)	163,397	16,170	87,702	84,498	55,552	23,179	27,505
Coke Oven Gas Consumption	22,033	16,557	16,649	16,239	15,336	9,951	14,233
Blast Furnace Gas Production	1,439,380	1,299,980	1,236,526	1,173,588	1,104,674	672,486	911,180
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	21,897	28,077	10,826	7,848	10,403
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	559	525	528	373	546
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	97,178	93,148	87,327	55,831	80,626
Blast Furnace Gas Consumption	1,414,778	1,295,520	1,231,021	1,168,444	1,099,845	670,051	907,999

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 C 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 (e.g., 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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-66 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 45.5 and 63.3 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 17 percent above the emission estimate of 54.3 Tg CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production were estimated to be 0.5 Tg 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 0.5 Tg CO_2 Eq.

Table 4-66: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (Tg. CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate**	**Uncertainty Range Relative to Emission Estimate**[a]			
		(Tg CO_2 Eq.)	**(Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Metallurgical Coke & Iron and Steel Production	CO_2	54.3	45.5	63.3	-16%	+17%
Metallurgical Coke & Iron and Steel Production	CH_4	0.5	0.4	0.6	-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 time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Iron and Steel Production category involve research into the availability of iron and steel production data, and analyzing data reported to EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Iron and Steel Production 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.[140]

Additional improvements include attributing emissions 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.

Recalculations Discussion

The average heat content of natural gas consumed in the United States is obtained directly from EIA and varies slightly each year (from 1024 to 1030 MMBTU/million cubic feet). In the previous Inventory, the 2009 heat content of natural gas was incorrectly applied to all historical years, so the year-to-year variation in the heat content of natural gas was not captured. This issue has been corrected for years 1990 through 2009 and decreased emissions for iron and steel production by less than 0.2 percent each year relative to the previous report.

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

4.15. Ferroalloy Production (IPCC Source Category 2C2)

Carbon dioxide and CH_4 are emitted from the production of several ferroalloys. Ferroalloys are composites of iron and other elements such as silicon, manganese, and chromium. When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Estimates from two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (about 98 percent silicon), and miscellaneous alloys (36 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. Subsequently, government information disclosure rules prevent the publication of production data for these production facilities.

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 is given below:

$$\mathrm{Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO}$$

While most of the C 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.

Emissions of CO_2 from ferroalloy production in 2010 were 1.5 Tg CO_2 Eq. (1,469 Gg) (see Table 4-67 and Table 4-68), which is a 32 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2010 were 0.01 Tg CO_2 Eq. (0.406 Gg), which is a 40 percent decrease since 1990.

Table 4-67: CO_2 and CH_4 Emissions from Ferroalloy Production (Tg CO_2 Eq.)

Year	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	2.2		1.4	1.5	1.6	1.6	1.5	1.5
CH_4	+		+	+	+	+	+	+
Total	**2.2**		**1.4**	**1.5**	**1.6**	**1.6**	**1.6**	**1.6**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 4-68: CO_2 and CH_4 Emissions from Ferroalloy Production (Gg)

Year	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	2,152		1,392	1,505	1,552	1,599	1,469	1,469
CH_4	1		+	+	+	+	+	+

Methodology

Emissions of CO_2 and CH_4 from ferroalloy production were calculated using a Tier 1 method from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), specifically by multiplying annual ferroalloy production by material-specific default emission factors provided by IPCC (2006). 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 (2.5 metric tons CO_2/metric ton of alloy produced) and an emission factor for 65 percent silicon was applied for CH_4 (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 (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 using an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite C 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 2009 (see Table 4-69) were obtained from the USGS through personal communications with the USGS Silicon Commodity Specialist (Corathers 2011) and through the Minerals Yearbook: Silicon Annual Report (USGS 1991 through 2010). Because USGS does not provide estimates of silicon metal production for 2006-2009, 2005 production data are used. Until 1999, the USGS reported production of ferrosilicon containing 25 to 55 percent silicon separately from production of miscellaneous alloys containing 32 to 65 percent silicon; beginning in 1999, the USGS reported these as a single category (see Table 4-69). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993). Due to the unavailability of 2010 data at the time of publication of this report, 2009 data is being used as a proxy.

Table 4-69: 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
2006	164,000	88,700	148,000	NA
2007	180,000	90,600	148,000	NA
2008	193,000	94,000	148,000	NA
2009	123,932	104,855	148,000	NA
2009	123,932	104,855	148,000	NA

NA (Not Available)

Uncertainty and Time-Series Consistency

Although some ferroalloys may be produced using wood or other biomass as a C source, 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 C is of biogenic origin.[141] 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 reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

Also, annual ferroalloy production is now reported by the USGS in three broad categories: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal. It was assumed that the IPCC emission factors apply to all of the ferroalloy production processes, including miscellaneous alloys. Finally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing company proprietary data. Emissions from this production category, therefore, were not estimated.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-70. Ferroalloy production CO_2 emissions were estimated to be between 1.3 and 1.7 Tg 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 1.5 Tg 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 Tg CO_2 Eq.

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[141] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

Table 4-70: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.5	1.3	1.7	-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 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Ferroalloy Production category involve research into the availability of ferroalloy production data, and analyzing data reported to EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Ferroalloy Production 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.[142] Additionally, research will be conducted to determine whether data are available concerning raw material consumption (e.g., coal coke, limestone and dolomite flux, etc.) for inclusion in ferroalloy production emission estimates.

4.16. 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 last reporting, the United States was the fifth largest producer of primary aluminum, with approximately four percent of the world total (USGS 2011). 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 carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, most of this carbon is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 3.0 Tg CO_2 Eq. (3,005 Gg) in 2010 (see Table 4-71). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for here and not under the CO_2 from Fossil Fuel Combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-71: CO_2 Emissions from Aluminum Production (Tg CO_2 Eq. and Gg)

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

Year	Tg CO_2 Eq.	Gg
1990	6.8	6,831
2000	6.1	6,086
2005	4.1	4,142
2006	3.8	3,801
2007	4.3	4,251
2008	4.5	4,477
2009	3.0	3,009
2010	3.0	3,005

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 carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase.

Since 1990, emissions of CF_4 and C_2F_6 have declined by 92 percent and 89 percent, respectively, to 1.26 Tg CO_2 Eq. of CF_4 (0.19 Gg) and 0.30 Tg CO_2 Eq. of C_2F_6 (0.033 Gg) in 2010, as shown in Table 4-72 and Table 4-73. 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. Since 1990, aluminum production has declined by 57 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 80 percent.

Table 4-72: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	15.9	2.7	18.5
2000	7.8	0.8	8.6
2005	2.5	0.4	3.0
2006	2.1	0.4	2.5
2007	3.2	0.6	3.8
2008	2.2	0.5	2.7
2009	1.3	0.3	1.6
2010	1.3	0.3	1.6

Note: Totals may not sum due to independent rounding.

Table 4-73: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.4	0.3
2000	1.2	0.1
2005	0.4	+
2006	0.3	+
2007	0.5	0.1
2008	0.3	0.1
2009	0.2	+
2010	0.2	+

+ Does not exceed 0.05 Gg.

In 2010, U.S. primary aluminum production totaled approximately 1.7 million metric tons, less than half a percent increase from 2009 production levels (USAA 2011a). In 2010, five companies managed production at nine operational primary aluminum smelters. Two smelters were permanently closed in 2010. An additional five smelters were temporarily idled in 2010 (USGS 2011). During 2010, monthly U.S. primary aluminum production was less in January through April, and greater from June through December when compared to the corresponding month in 2009 (USAA 2011a).

For 2011, total production was approximately 2.0 million metric tons compared to 1.7 million metric tons for the same period in 2010, a 15 percent increase (USAA 2012). Based on the increase in production, process CO_2 and PFC emissions are likely to be greater in 2011 compared to 2010 given no significant changes in process controls at operational facilities.

Methodology

CO_2 emissions released during aluminum production were estimated by combining individual partner reported data with process-specific emissions modeling. These estimates are based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the carbon anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or, (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all carbon in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a carbon consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This 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.

Starting in 2010, primary aluminum smelters reported process emissions data to EPA under Subpart F of the EPA's GHGRP. The data reported under Subpart F include facility-specific process emission totals for: carbon dioxide (CO_2) from anode/paste consumption plus anode baking, and perfluoromethane (CF_4) and perfluroethane (C_2F_6) from anode effects. As a result, in 2010, these smelters were requested not to report any data to EPA under the VAIP. At the time of writing, the aggregated emission totals are not published, so are not available for reporting here.

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, 3 out of 13 operating smelters in 2009, and 0 out of 9 operating smelters in 2010. For years where CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., industry default) values.

In the absence of any previous smelter specific process data (i.e., 1 out of 9 smelters in 2010, 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).

Aluminum production data for 0 out of 9 operating smelters were reported under the VAIP in 2010. Between 1990 and 2009, production data were provided 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 (USAA 2011a), with allocation to specific smelters based on reported production capacities (USGS 2011).

PFC emissions from aluminum production were estimated using a per-unit production emission factor that is expressed as a function of operating parameters (anode effect frequency and duration), as follows:

$$\text{PFC } (CF_4 \text{ or } C_2F_6) \text{ kg/metric ton Al} = S \times (\text{Anode Effect Minutes/Cell-Day})$$

where,

$$S = \text{Slope coefficient ((kg PFC/metric ton Al)/(Anode Effect Minutes/Cell-Day))}$$
$$(\text{Anode Effect Minutes/Cell-Day}) = (\text{Anode Effect Frequency/Cell-Day}) \times \text{Anode Effect Duration (minutes)}$$

This approach corresponds to either the Tier 3 or the Tier 2 approach in the 2006 IPCC Guidelines, depending upon whether the slope-coefficient is smelter-specific (Tier 3) or technology-specific (Tier 2). For 1990 through 2010, 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 2000, 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 2010, smelter-specific anode effect data were available for smelters representing between 0 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., 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 2010, smelter-specific production data were available for smelters representing between 0 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range, except for 2010 when no production data was available.) 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.

National primary aluminum production data for 2010 were obtained via the Aluminum Association (USAA 2011a). For 1990 through 2001, and 2006 (see Table 4-74) 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 2009 national aluminum production data were obtained from the USAA's Primary Aluminum Statistics (USAA 2004, 2005, 2006, 2008, 2009, 2010).

Table 4-74: Production of Primary Aluminum (Gg)

Year	Gg
1990	4,048
2000	3,668
2005	2,478
2006	2,284
2007	2,560
2008	2,659
2009	1,727
2010	1,727

Uncertainty and Time Series Consistency

The overall uncertainties associated with the 2010 CO_2, CF_4, and C_2F_6 emission estimates were calculated using Approach 2, as defined by IPCC (2006). For CO_2, uncertainty was assigned to each of the parameters used to estimate CO_2 emissions. Uncertainty surrounding estimated production data was assumed to have a triangular distribution with a minimum value of zero and a maximum value corresponding to the reported production capacity (USGS 2011). For additional variables, such as net carbon consumption, and sulfur and ash content in baked anodes, estimates for uncertainties associated with reported and default data were obtained from IPCC (2006). A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2 emission estimate for the U.S. aluminum industry as a whole, and the results are provided below.

To estimate the uncertainty associated with emissions of CF_4 and C_2F_6, the uncertainties associated with three variables were estimated for each smelter: (1) the quantity of aluminum produced, (2) the anode effect minutes per cell day (which may be reported directly or calculated as the product of anode effect frequency and anode effect duration), and, (3) the smelter- or technology-specific slope coefficient. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emission estimate for each smelter and for the U.S. aluminum industry as a whole.

The results of this quantitative uncertainty analysis are summarized in Table 4-75. Aluminum production-related CO_2 emissions were estimated to be between 1.54 and 3.06 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 49 percent below to 2 percent above the emission estimate of 3.01 Tg CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 0.63 and 1.33 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 50 percent below to 6 percent above the emission estimate of 1.26 Tg CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.11 and 0.35 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 62 percent below to 15 percent above the emission estimate of 0.30 Tg CO_2 Eq.

Table 4-75: Tier 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to 2010 Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	3.0	1.5	3.1	−49%	+2%
Aluminum Production	CF_4	1.3	0.6	1.3	−50%	+6%
Aluminum Production	C_2F_6	0.3	0.1	0.4	−62%	+15%

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

The 2010 emission estimate was developed using either company-wide or site-specific PFC slope coefficients for all but 1 of the 9 operating smelters where default IPCC (2006) slope data was used. In some cases, where smelters are owned by one company, data have been reported on a company-wide basis as totals or weighted averages. Consequently, in the Monte Carlo analysis, uncertainties in anode effect minutes per cell day, slope coefficients, and aluminum production have been applied to the company as a whole and not to each smelter. This probably overestimates the uncertainty associated with the cumulative emissions from these smelters, because errors that were in fact independent were treated as if they were correlated. It is therefore likely that the uncertainties calculated above for the total U.S. 2010 emission estimates for CF_4 and C_2F_6 are also overestimated.

Recalculations

In the current Inventory, methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

In the current Inventory, reported production data for one smelter was updated for the years 1990, 2000, and 2003. These data were used to recalculate emissions, and resulted in a difference of less than one percent for each of those years for total PFC emissions, relative to the previous report.

Planned Improvements

Future improvements to the Ferroalloy Production category involve research into the availability of ferroalloy production data, and analyzing data reported to EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Ferroalloy Production 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.[143]

4.17. Magnesium Production and Processing (IPCC Source Category 2C4) - To Be Updated

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 twenty-five 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. Although alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 and dilute SO_2 systems can be used, many facilities in the United States are still using traditional SF_6 cover gas systems.

The magnesium industry emitted 1.1 Tg CO_2 Eq. (0.04 Gg) of SF_6 in 2009, representing a decrease of approximately 45 percent from 2008 emissions (See Table 4-72). The decrease can be attributed to die casting facilities in the United States closing or halting production due to reduced demand from the American auto industry and other industrial sectors (USGS 2010a). Production associated with primary and secondary facilities also dropped in 2009. The significant reduction in emissions can also be attributed to industry efforts to switch to cover gas alternatives, such as sulfur dioxide, as part of the EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry.

Table 4-76: SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	5.4	0.2
2000	3.0	0.1
2005	2.9	0.1
2006	2.9	0.1
2007	2.6	0.1
2008	1.9	0.1
2009	1.1	0.04

Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. The Partnership started in 1999 and, currently, participating companies represent 100 percent of U.S. primary and secondary production and 90 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). Absolute emissions for 1999 through 2009 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. When a partner did not report emissions, they were estimated based on the metal processed and

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

emission rate reported by that partner in previous and (if available) subsequent years. Where data for subsequent years was not available, metal production and emissions rates were extrapolated based on the trend shown by partners reporting in the current and previous years. When it was determined a Partner is no longer in production, their metal production and emissions rates were set to zero if no activity information was available; in one case a partner that closed mid-year was estimated to have produced 50 percent of the metal from the prior year.

Emission factors for 2002 to 2006 for sand casting activities were also acquired through the Partnership. For 2007, 2008 and 2009, the sand casting partner did not report and the reported emission factor from 2005 was utilized as being representative of the industry. The 1999 through 2009 emissions from casting operations (other than die) 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. The emission factors for casting activities are provided below in Table 4-77. The emission factors for primary production, secondary production and sand casting are withheld 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. U.S. magnesium consumption (casting) data from 1990 through 2009 were available from the USGS (USGS 2002, 2003, 2005, 2006, 2007, 2008, 2010).

Table 4-77: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting	Permanent Mold	Wrought	Anodes
1999	2.14[a]	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	0.81	2	1	1
2005	0.79	2	1	1
2006	0.86	2	1	1
2007	0.67	2	1	1
2008	1.15[b]	2	1	1
2009	1.77[b]	2	1	1

[a] This is a weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that did not participate in the Partnership in 1999. These die casters were assumed to be similar to partners that 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. In later years, die casters participating in the Partnership accounted for all U.S. die casting tracked by USGS.

[b] The emission factor for die casting increased significantly between 2007 and 2008, and again between 2008 and 2009. These increases occurred for two reasons. First, one of the die casters with a significant share of U.S. production that had used SF_6 as a cover gas and that had maintained a relatively low emission rate began using an alternative cover gas in 2008. Since the SF_6 emission factor provided here is based only on die casting operations that use SF_6 as a cover gas, the removal of the low-emitting die caster from the SF_6-using group increased the weighted average emission rate of that group. Second, one SF_6-using die caster experienced a significant leak in its cover gas distribution system in 2009 that resulted in an abnormally high SF_6 emission rate.

To estimate emissions for 1990 through 1998, industry emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. The primary production emission factors were 1.2 kg per metric ton for 1990 through 1993, and 1.1 kg per metric ton for 1994 through 1997. These factors were based on information provided by U.S. primary producers. For die casting, an emission factor of 4.1 kg per metric ton was used for the period 1990 through 1996. This factor was drawn from an international survey of die casters (Gjestland & Magers 1996). For 1996 through 1998, the emission factors for primary production and die casting were 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 2002 through 2009 were provided by the Magnesium Partnership participants, and 1990 through 2001 emission factors for this process were assumed to have been the same as the 2002 emission factor. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average partner value. 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 4-77.

Uncertainty

To estimate the uncertainty surrounding the estimated 2009 SF_6 emissions from magnesium production and processing, the uncertainties associated with three variables were estimated (1) emissions reported by magnesium producers and processors that participate in the Magnesium Partnership, (2) emissions estimated for magnesium producers and processors that participate in the Partnership but did not report this year, and (3) emissions estimated for magnesium producers and processors that do not participate in the Partnership. An uncertainty of 5 percent was assigned to the data reported by each participant in the Partnership. If partners did not report emissions data during the current reporting year, SF_6 emissions data were estimated using available emission factor and production information reported in prior years; the extrapolation was based on the average trend for partners reporting in the current reporting year and the year prior. The uncertainty associated with the SF_6 usage estimate generated from the extrapolated emission factor and production information was estimated to be 30 percent for each year of extrapolation. The lone sand casting partner did not report in the past two reporting years 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 52 percent. For those industry processes that are not represented in 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 4-77). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with sand casting activities utilized a partner-reported emission factor with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Recent 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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-78. SF_6 emissions associated with magnesium production and processing were estimated to be between 1.01 and 1.10 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 6 percent below to 5 percent above the 2008 emission estimate of 1.05 Tg CO_2 Eq.

Table 4-78: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2009 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Magnesium Production	SF_6	1.05	1.01	1.10	-4%	+4%

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

Recalculations Discussion

The uncertainty estimates for 2009 are lower relative to the previous inventory uncertainty estimate for 2008 emissions, which is likely due to the fact that emission estimates for 2009 are based more on actual reported data than emission estimates for 2008 were in the 1990-2008 inventory, with two emission sources using projected (highly uncertain) estimates.

Planned Improvements

Cover gas research conducted by the EPA 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 for National Greenhouse Gas Inventories (IPCC 2006)) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of IPCC Guidelines to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the inventory methodology. Another issue that will be addressed in future inventories is the likely adoption of alternate cover gases by U.S. magnesium producers and processors. These cover gases, which include AM-cover™ (containing HFC-134a) and Novec™ 612, have lower GWPs than SF_6, and tend to quickly degrade during their exposure to the molten metal. Magnesium producers and processors have already begun using these cover gases for 2006 through 2009 in a limited fashion; because the amounts being used by companies on the whole are low enough that they have a minor effect on the overall emissions from the industry, these emissions are only being monitored and recorded at this time.

4.18. Zinc Production (IPCC Source Category 2C5)

Zinc production in the United States consists of both primary and secondary processes. 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). 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).

During one secondary technique, 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 added to the electric retort furnace reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser.

In the other secondary technique or Waelz kiln process, EAF dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent—often 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. Through this process, approximately 0.33 metric ton of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

In 2010, U.S. primary and secondary refined zinc production were estimated to total 205,000 metric tons (USGS 2011a), which was far below historical levels and near 2009 levels despite the general improvement in the U.S. economy in 2010 (see Table 4-75). This was largely due to an explosion at one of the biggest secondary refined zinc facilities in the United States (Horsehead Corporation's Monaca facility), which resulted in a temporary shutdown at the facility (Horsehead Corp. 2010b).

Emissions of CO_2 from zinc production in 2010 were estimated to be 1.17 Tg CO_2 Eq. (1,168 Gg) (see Table 4-80). All 2010 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 2010, emissions were estimated to be 85 percent higher than they were in 1990.

Table 4-79: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	95,708
2005	191,120	156,000

2006	113,000	156,000
2007	121,000	157,000
2008	125,000	161,000
2009	94,000	109,000
2010	120,000	85,000

Table 4-76: CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.6	632
2005	1.0	1030
2006	1.0	1030
2007	1.0	1025
2008	1.2	1159
2009	0.9	943
2010	1.2	1168

Methodology

Non-energy CO_2 emissions from zinc production result from the electrothermic and Waelz kiln secondary production processes, which both use metallurgical coke or other C-based materials as reductants. The methods used to estimate emissions from these processes are based on Tier 1 methods from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The Tier 1 emission factors provided by IPCC (2006) 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 (2006) does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were applied to zinc produced from electrothermic processes.

For Waelz kiln-based production, IPCC (2006) 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, 1.19 metric tons coke/metric ton zinc produced (Viklund-White 2000), and the following equation:

$$EF_{\text{Waelz Kiln}} = \frac{1.19\,\text{metric tons coke}}{\text{metric tons zinc}} \times \frac{0.85\,\text{metric tons C}}{\text{metric tons coke}} \times \frac{3.67\,\text{metric tons } CO_2}{\text{metric tons C}} = \frac{3.70\,\text{metric tons } CO_2}{\text{metric tons zinc}}$$

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, 0.4 metric tons coke/metric ton EAF dust consumed (Viklund-White 2000), and the following equation:

$$EF_{\text{EAF Dust}} = \frac{0.4\,\text{metric tons coke}}{\text{metric tons EAF dust}} \times \frac{0.85\,\text{metric tons C}}{\text{metric tons coke}} \times \frac{3.67\,\text{metric tons } CO_2}{\text{metric tons C}} = \frac{1.24\,\text{metric tons } CO_2}{\text{metric tons EAF Dust}}$$

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 Corp. 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.

The total amount of EAF dust consumed by Horsehead at their Waelz kilns was available from Horsehead financial reports for years 2006 through 2010 (Horsehead Corp. 2008, 2010a, and 2011). 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 1994 through 2010). 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 PIZO's facility in 2009 and 2010 and Steel Dust Recycling's facility for 2008, 2009, and 2010 (the only years these facilities have been in operation) was not publically available. Therefore, these consumption values were estimated by calculating the 2008, 2009, and 2010 capacity utilization of Horsehead's Waelz kilns and multiplying this utilization ratio by the capacities of the PIZO and Steel Dust Recycling facilities, which were available from the companies (PIZO 2011 and Steel Dust Recycling LLC 2011). 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 2010 (Horsehead Corp. 2008 and 2011). 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 1994 through 2010). 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 estimate of the amount of EAF dust consumed at a Waelz kiln facility operated in Alabama by Steel Dust Recycling LLC. Since actual EAF dust consumption information is not available for the Steel Dust Recycling LLC facility, 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). Therefore, there is uncertainty associated with the assumption that the capacity utilization of Steel Dust Recycling LLC's Waelz kiln facility is equal to the capacity utilization of Horsehead's Waelz kiln facility. 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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-80. Zinc production CO_2 emissions were estimated to be between 1.0 and 1.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below and 19 percent above the emission estimate of 1.2 Tg CO_2 Eq.

Table 4-80: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	1.2	1.0	1.4	-17%	+19%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Zinc Production category involve research into the availability of Zinc Production data, and examining data reported to EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Zinc Production 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.[144]

Recalculations Discussion

In 2009, PIZO Technologies LLC commissioned an EAF dust consuming secondary production facility. The 2009 EAF dust consumption from this facility was not captured in the previous Inventory. In addition, the EAF dust consumption data provided from Horsehead Corp for years 2006 through 2009 were incorrectly considered to be in metric tons in the previous Inventory when the data were actually provided in short tons (this also impacted 1990 through 2005 EAF dust consumption data that are estimated based on the 2006 estimate). Both of these issues have been corrected in the current Inventory and decreased 1990 through 2009 emissions from zinc production by an average of 5.2 percent per year.

4.19. 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). Primary lead production, in the form of direct smelting, occurs at a just a single plant in Missouri. Secondary production largely involves the recycling of lead acid batteries at approximately 20 separate smelters in the United States. Fourteen of those secondary smelters have annual capacities of 15,000 tons or more and were collectively responsible for 99 percent of secondary lead production in 2010 (USGS 2011b). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2009, secondary lead production accounted for approximately 92 percent of total lead production (USGS 2011a).

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). U.S. primary lead production increased by 24 percent from 2009 to 2010, and has decreased by 72 percent since 1990 (USGS 1995, 2011a, 2011c).

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). U.S. secondary lead production increased from 2009 to 2010 by 3 percent, and has increased by 24 percent since 1990 (USGS 1995 and 2011a).

In 2010, U.S. primary and secondary lead production totaled 1,255,000 metric tons (USGS 2011a). The resulting emissions of CO_2 from 2010 production were estimated to be 0.5 Tg CO_2 Eq. (542 Gg) (see Table 4-81). The majority of 2010 lead production is from secondary processes, which accounted for 95 percent of total 2010 CO_2 emissions. At last reporting, the United States was the third largest mine producer of lead in the world, behind

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

China and Australia, accounting for 11 percent of world production in 2009 (USGS 2011c).

Table 4-81: CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.5	516
2005	0.6	553
2006	0.6	560
2007	0.6	562
2008	0.6	551
2009	0.5	525
2010	0.5	542

After a steady increase in total emissions from 1995 to 2000, total emissions have gradually decreased since 2000 but were still 5 percent greater in 2010 than in 1990. Although primary production has decreased significantly (75 percent since 1990), secondary production has increased by about 20 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 1994 and 2011a).

Methodology

Non-energy CO_2 emissions from lead production result from primary and secondary production processes that use metallurgical coke or other C-based materials as reductants. The methods used to estimate emissions for lead production are based on Tier 1 methods from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). 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). 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 2009 activity data for primary and secondary lead production (see Table 4-82) were obtained through the USGS Mineral Yearbook: Lead (USGS 1994 through 2011c), while 2010 activity was obtained through direct correspondence with USGS (USGS 2011a).

Table 4-82: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
2005	143,000	1,150,000
2006	153,000	1,160,000
2007	123,000	1,180,000
2008	135,000	1,150,000
2009	103,000	1,110,000
2010	115,000	1,140,000

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 averages the values provided by three other studies (Dutrizac et al. 2000, Morris et al. 1983, Ullman 1997). For secondary production, Sjardin

(2003) adds 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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-83. Lead production CO_2 emissions were estimated to be between 0.5 and 0.6 Tg 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 Tg CO_2 Eq.

Table 4-83: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate**[a]			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Lead Production	CO_2	0.5	0.5	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 time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements to the Lead Production category involve research into the availability of lead production data, and analyzing data reported to EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Lead Production 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.[145]

4.20. HCFC-22 Production (IPCC Source Category 2E1) - To Be Updated

Trifluoromethane (HFC-23 or CHF_3) is generated as a by-product 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. 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.[146] 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.

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

[146] 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]

Emissions of HFC-23 in 2009 were estimated to be 5.4 Tg CO_2 Eq. (0.5 Gg) (Table 4-84). This quantity represents a 60 percent decrease from 2008 emissions and a 85 percent decline from 1990 emissions. The decrease from 2008 emissions was caused by a 27 percent decrease in HCFC-22 production and a 46 percent decrease in the HFC-23 emission rate. The decline from 1990 emissions is due to a 34 percent decrease in HCFC-22 production and a 78 percent decrease in the HFC-23 emission rate since 1990. The decrease in the emission rate is primarily attributable to five 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, and (e) another plant began destroying HFC-23. All three HCFC-22 production plants operating in the United States in 2009 used thermal oxidation to significantly lower their HFC-23 emissions.

Table 4-84: HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	36.4	3
2000	28.6	2
2005	15.8	1
2006	13.8	1
2007	17.0	1
2008	13.6	1
2009	5.4	0.46

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 for National Greenhouse Gas Inventories (IPCC 2006) were used. 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 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.

In most years, including 2010, an industry association aggregates and reports to EPA country-level estimates of HCFC-22 production and HFC-23 emissions (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010). However, in 1997 and 2008, EPA (through a contractor) performed comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production (RTI 1997; RTI 2008). These reviews enabled EPA to review, update, and where necessary, correct U.S. totals, and also to perform plant-level uncertainty analyses (Monte-Carlo simulations) for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-85.

Table 4-85: HCFC-22 Production (Gg)

Year	Gg
1990	139
2000	186

2005	156
2006	154
2007	162
2008	126
2009	91

Uncertainty and Time Series Consistency

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo 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.

Because plant-level emissions data for 2009 were not available, the relative errors yielded by the Monte Carlo simulation for 2006 were applied to the U.S. emission estimate for 2009. The resulting estimates of absolute uncertainty are likely to be 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 2008 and 2009 (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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-86. HFC-23 emissions from HCFC-22 production were estimated to be between 5.0 and 5.9 Tg CO_2 Eq. at the 95percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 5.4 Tg CO_2 Eq.

Table 4-86: Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2009 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
HCFC-22 Production	HFC-23	5.4	5.0	5.9	-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 2009. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Beginning in 2010, all U.S. HCFC-22 production facilities are required to calculate and report their greenhouse gas emissions to EPA through its Greenhouse Gas Reporting Program. Data collected under this program will be used in future inventories to improve the calculation of national emissions from HCFC-22 production.

4.21. 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.[147] 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 4-87 and Table 4-88.

Table 4-87: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.)

Gas	1990	2005	2006	2007	2008	2009	2010
HFC-23	+	+	+	+	+	+	+
HFC-32	+	0.3	0.6	1.0	1.3	1.6	2.4
HFC-125	+	10.1	12.5	15.1	18.2	21.6	27.1
HFC-134a	+	75.1	75.0	72.3	69.3	66.7	66.7
HFC-143a	+	12.2	14.4	16.7	19.2	22.0	25.1
HFC-236fa	+	0.8	0.8	0.9	0.9	0.9	0.9
CF_4	+	+	+	+	+	+	+
Others*	0.3	5.6	6.0	6.3	6.7	7.0	7.4
Total	**0.3**	**104.2**	**109.3**	**112.3**	**115.5**	**120.0**	**129.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

* Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, 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 4-88: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	2005	2006	2007	2008	2009	2010
HFC-23	+	1	1	1	2	2	2
HFC-32	+	505	970	1,463	1,974	2,535	3,751
HFC-125	+	3,618	4,451	5,391	6,483	7,725	9,673
HFC-134a	+	57,777	57,728	55,602	53,293	51,285	51,327
HFC-143a	+	3,200	3,782	4,402	5,044	5,798	6,607
HFC-236fa	+	125	131	136	141	144	146
CF_4	+	2	2	2	2	2	3
Others*	M	M	M	M	M	M	M

M (Mixture of Gases)

+ Does not exceed 0.5 Mg

* Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, 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.[148] 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 129.7 Tg CO_2 Eq. in 2010. This increase was in large part the result of efforts to phase out CFCs and other

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[147] [42 U.S.C § 7671, CAA § 601]

[148] R-404A contains HFC-125, HFC-143a, and HFC-134a.

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 4-89 presents emissions of HFCs and PFCs as ODS substitutes by end-use sector for 1990 through 2010. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2010 include refrigeration and air-conditioning (112.4 Tg CO_2 Eq., or approximately 87 percent), aerosols (9.3 Tg CO_2 Eq., or approximately 7 percent), and foams (5.4 Tg CO_2 Eq., or approximately 4 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (47.3 Tg CO_2 Eq.), followed by refrigerated retail food and transport. Each of the end-use sectors is described in more detail below.

Table 4-89: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.) by Sector

Gas	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Refrigeration/Air Conditioning	+		92.9	97.4	99.6	102.1	104.6	112.4
Aerosols	0.3		7.3	7.7	8.2	8.6	9.1	9.3
Foams	+		1.9	2.1	2.3	2.5	3.9	5.4
Solvents	+		1.3	1.3	1.3	1.3	1.3	1.3
Fire Protection	+		0.5	0.6	0.7	0.7	0.8	0.9
Total	**0.3**		**104.0**	**109.1**	**112.0**	**115.2**	**119.7**	**129.4**

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.[149] R-404A, and R-507A.[150] 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.

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[149] R-410A contains HFC-32 and HFC-125.

[150] R-507A, also called R-507, contains HFC-125 and HFC-143a.

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-4310mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of 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 nearly 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 3.8.

Uncertainty and Time-Series Consistency- To Be Updated

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 nearly 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 5 other end-uses. These 26 end-uses comprise 97 percent of the total emissions. 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 retail food equipment and refrigerated transport, as well as the percent of non-MDI aerosol propellant that is HFC-152a.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-90. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 111.8 and 129.3 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below to 8 percent above the emission estimate of 120.0 Tg CO_2 Eq.

Table 4-90: Tier 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (Tg CO_2 Eq. and Percent)

Source	Gases	2009 Emission Estimate (Tg CO_2 Eq.)[a]	Uncertainty Range Relative to Emission Estimate[b] (Tg CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[b] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	117.1	109.0	126.5	-7%	+8%

[a] 2009 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, 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 estimates reported in this table.

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

Recalculations Discussion

A review of the window units and residential unitary air conditioning end-uses led to minor revisions in the assumed transition scenarios. Overall, these changes to the Vintaging Model had negligible effects on estimates of greenhouse gas emissions across the time series.

4.22. Semiconductor Manufacture (IPCC Source Category 2F6) - To Be Updated

The semiconductor industry uses multiple long-lived fluorinated 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), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), 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 500 semiconductor products (devices or chips) may require as many as 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.

For 2009, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 5.3 Tg CO_2 Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 4-91 and Table 4-92 below for years 1990, 2000 and the period 2005 to 2009. The rapid growth of this industry and the increasing complexity (growing number of layers)[151] of semiconductor products led to an increase in emissions of 148 percent between 1990 and 1999, when emissions peaked at 7.2 Tg CO_2 Eq. The emissions growth rate began to slow after 1998, and emissions declined by 26 percent between 1999 and 2009. Together, industrial growth and adoption of emissions reduction technologies, including but not limited to abatement technologies, resulted in a net increase in emissions of 83 percent between 1990 and 2009.

Table 4-91: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq.)

Year	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**
CF_4	0.7	1.8	1.1	1.2	1.3	1.4	1.5
C_2F_6	1.5	3.0	2.0	2.2	2.3	2.4	2.5
C_3F_8	0.0	0.1	0.0	0.0	0.0	0.1	0.0
C_4F_8	0.0	0.0	0.1	0.1	0.1	0.1	0.0
HFC-23	0.2	0.3	0.2	0.3	0.3	0.3	0.3
SF_6	0.5	1.1	1.0	1.0	0.8	0.9	1.0
NF_3*	0.0	0.2	0.4	0.7	0.5	0.6	0.5
Total	**2.9**	**6.2**	**4.4**	**4.7**	**4.8**	**5.1**	**5.3**

Note: Totals may not sum due to independent rounding.
* NF_3 emissions are presented for informational purposes, using the AR4 GWP of 17,200, and are not included in totals.

Table 4-92: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Mg)

Year	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**
CF_4	115	281	168	181	198	216	227
C_2F_6	160	321	216	240	249	261	271
C_3F_8	0	18	5	5	6	13	5
C_4F_8	0	0	13	13	7	7	4
HFC-23	15	23	18	22	23	25	28

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[151] 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.

SF_6	22	45	40	40	34	36	40
NF_3	3	11	26	40	30	33	30

Methodology

Emissions are based on Partner reported emissions data received through the EPA's PFC Reduction/Climate Partnership and the EPA's PFC Emissions Vintage Model (PEVM), a model which estimates industry emissions in the absence of emission control strategies (Burton and Beizaie 2001).[152] The availability and applicability of Partner data differs across the 1990 through 2009 time series. Consequently, emissions from semiconductor manufacturing were estimated using four distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, and 2007 through 2009.

1990 through 1994

From 1990 through 1994, Partnership data was unavailable and emissions were modeled using the PEVM (Burton and Beizaie 2001).[153] 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 PFC 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.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[154] and (2) product type (discrete, memory or logic).[155] 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. 2010).

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

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[152] 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 report their PFC emissions to the EPA by way of a third party, which aggregates the emissions.

[153] 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.

[154] 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 the smallest feature sizes (65 nm) 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).

[155] 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.

world silicon consumption.

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 2010).

2000 through 2006

The emission estimate for the years 2000 through 2006—the period during which Partners began the consequential application of PFC-reduction measures—was estimated using a combination of Partner reported emissions and 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 and the method described above. This is because non-Partners are assumed not to have implemented any PFC-reduction measures, and PEVM models emissions without such measures. 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.[156,157] 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 2007 and Semiconductor Equipment and Materials Industry 2010).[158,159,160]

2007 through 2009

For the years 2007 through 2009, emissions were also estimated using a combination of Partner reported emissions

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[156] 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.

[157] Generally 5 percent or less of the fields needed to estimate TMLA shares are missing values in the World Fab Watch databases. In the 2007 World Fab Watch database used to generate the 2006 non-Partner TMLA capacity share, these missing values were replaced with the corresponding mean TMLA across fabs manufacturing similar classes of products. However, the impact of replacing missing values on the non-Partner TMLA capacity share was inconsequential.

[158] 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.

[159] 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.

[160] 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.

and PEVM modeled emissions; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2009 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[161] Second, the scope of the 2007 through 2009 estimates is expanded relative to the estimates for the years 2000 through 2006 to include emissions from Research and Development (R&D) fabs. This was feasible through the use of more detailed data published in the World Fab Forecast. PEVM databases are updated annually as described above. The published world average capacity utilization for 2007 and 2008 was used for production fabs while in 2008 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 the emissions in 2009 for non-partners. PEVM estimates were adjusted using technology weighted capacity shares that reflect relative influence of different utilization.

Gas-Specific Emissions

Two different approaches were also used to estimate the distribution of emissions of specific fluorinated gases. Before 1999, when 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. 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). For the 2000 through 2009 period, the 1990 through 1999 distribution was assumed to apply to the non-Partners. Partners, however, began reporting gas-specific emissions during this period. Thus, gas-specific emissions for 2000 through 2009 were estimated by adding the emissions reported by the Partners to those estimated for the non-Partners.

Data Sources

Partners estimate their emissions using a range of methods. For 2009, 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 for National Greenhouse Inventories (IPCC 2006). Data used to develop emission estimates are attributed in part to estimates provided by the members of the Partnership, and in part from data obtained from PEVM estimates. Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) World Fab Forecast (formerly World Fab Watch) database (1996 through 2009) (e.g., Semiconductor Materials and Equipment Industry, 2010). Actual world capacity utilizations for 2009 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA, 2009). Estimates of silicon consumed by linewidth from 1990 through 2009 were derived from information from VLSI Research, Inc. (2010), and the number of layers per linewidth was obtained from International Technology Roadmap for Semiconductors: 2006 Update (Burton and Beizaie 2001, ITRS 2007, ITRS 2008).

Uncertainty and Time Series Consistency

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The equation used to estimate uncertainty is:

$$\text{U.S. emissions} = \sum \text{Partnership gas-specific submittals} + [(\text{non-Partner share of World TMLA}) \times (\text{PEVM Emission Factor} \times \text{World TMLA})]$$

The Monte Carlo analysis results presented below relied on estimates of uncertainty attributed to the four quantities on the right side of the equation. Estimates of uncertainty for the four quantities were in turn developed using the estimated uncertainties associated with the individual inputs to each quantity, error propagation analysis, Monte Carlo simulation, and expert judgment. The relative uncertainty associated with World TMLA estimate in 2009 is

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[161] 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.

about ±10 percent, based on the uncertainty estimate obtained from discussions with VLSI, Inc. For the share of World layer-weighted silicon capacity accounted for by non-Partners, a relative uncertainty of ±8 percent was estimated based on a separate Monte Carlo simulation to account for the random occurrence of missing data in the World Fab Watch database. For the aggregate PFC emissions data supplied to the partnership, a relative uncertainty of ±50 percent was estimated for each gas-specific PFC emissions value reported by an individual Partner, and error propagation techniques were used to estimate uncertainty for total Partnership gas-specific submittals.[162] A relative uncertainty of approximately ±10 percent was estimated for the PEVM emission factor, based on the standard deviation of the 1996 to 1999 emission factors.[163] All estimates of uncertainties are given at 95-percent confidence intervals.

In developing estimates of uncertainty, consideration was also given to the nature and magnitude of the potential bias that World activity data (i.e., World TMLA) might have in its estimates of the number of layers associated with devices manufactured at each technology node. The result of a brief analysis indicated that U.S. TMLA overstates the average number of layers across all product categories and all manufacturing technologies for 2004 by 0.12 layers or 2.9 percent. The same upward bias is assumed for World TMLA, and is represented in the uncertainty analysis by deducting the absolute bias value from the World activity estimate when it is incorporated into the Monte Carlo analysis.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-93. The emissions estimate for total U.S. PFC emissions from semiconductor manufacturing were estimated to be between 4.8 and 5.9 Tg CO_2 Eq. at a 95 percent confidence level. This range represents 10 percent below to 11 percent above the 2009 emission estimate of 5.3 Tg 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: Tier 2 Quantitative Uncertainty Estimates for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2009 Emission Estimate[a] (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[b] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound[c]	**Upper Bound[c]**	**Lower Bound**	**Upper Bound**
Semiconductor Manufacture	HFC, PFC, and SF_6	5.3	4.8	5.9	−10%	+11%

[a] Because the uncertainty analysis covered all emissions (including NF_3), the emission estimate presented here does not match that shown in Table 4-91.
[b] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[c] 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 2009. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

With the exception of possible future updates to emission factors, the method to estimate non-Partner related emissions (i.e., PEVM) is not expected to change. Future improvements to the national emission estimates will primarily be associated with determining the portion of national emissions to attribute to Partner report totals (about 80 percent in recent years) and improvements in estimates of non-Partner totals. As the nature of the Partner reports change through time and industry-wide reduction efforts increase, consideration will be given to what emission reduction efforts—if any—are likely to be occurring at non-Partner facilities. Currently, none are assumed to occur.

Another point of consideration for future national emissions estimates is the inclusion of PFC emissions from heat transfer fluid (HTF) loss to the atmosphere and the production of photovoltaic cells (PVs). Heat transfer fluids, of

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[162] Error propagation resulted in Partnership gas-specific uncertainties ranging from 17 to 27 percent.
[163] The average of 1996 to 1999 emission factor is used to derive the PEVM emission factor.

which some are liquid perfluorinated compounds, are used during testing of semiconductor devices and, increasingly, are used to manage heat during the manufacture of semiconductor devices. Evaporation of these fluids is a source of emissions (EPA 2006). PFCs are also used during manufacture of PV cells that use silicon technology, specifically, crystalline, polycrystalline, and amorphous silicon technologies. PV manufacture is growing in the United States, and therefore may be expected to constitute a growing share of U.S. PFC emissions from the electronics sector.

4.23. Electrical Transmission and Distribution (IPCC Source Category 2F7)

The largest use of 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. Sulfur hexafluoride 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 11.8 Tg CO_2 Eq. (0.5 Gg) in 2010. This quantity represents a 56 percent decrease from the estimate for 1990 (see Table 4-94 and Table 4-95). This decrease is believed to have two causes: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.

Table 4-94: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (Tg CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	26.3	0.3	26.7
2000	14.4	0.7	15.1
2005	13.1	0.8	13.9
2006	12.2	0.8	13.0
2007	11.5	0.7	12.2
2008	11.1	1.1	12.2
2009	11.3	0.6	11.8
2010	11.0	0.8	11.8

Note: Totals may not sum due to independent rounding.

Table 4-95: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (Gg)

Year	Emissions
1990	1.1
2000	0.6
2005	0.6
2006	0.5
2007	0.5
2008	0.5
2009	0.5
2010	0.5

Methodology

The estimates of emissions from Electric 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.

1999 through 2010 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2010 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; and, (2) the relationship between emissions and utilities' transmission miles as reported in the 2001, 2004, 2007, and 2010 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV.) Over the period from 1999 to 2010, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership, represented between 43 percent and 48 percent of total U.S. transmission miles. For each year, the emissions reported by or estimated for Partner utilities were added to the emissions estimated for utilities that have never participated in the Partnership (i.e., non-Partners).[164]

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 2010, non-reporting Partners accounted for approximately 16 percent of the total emissions attributed to Partner utilities.

Emissions from non-Partners in every year since 1999 were estimated using the results of a regression analysis that showed that the emissions from reporting utilities were most strongly correlated with their transmission miles. The results of this analysis are not surprising given that, in the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV. The equations were developed based on the 1999 SF_6 emissions reported by a subset of 42 Partner utilities (representing approximately 23 percent of U.S. transmission miles) and 2000 transmission mileage data obtained from the 2001 UDI Directory of Electric Power Producers and Distributors (UDI 2001). Two equations were developed, one for small and one for large utilities (i.e., with fewer or more 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 small and large transmission networks. The same equations were used to estimate non-Partner emissions in 1999 and every year thereafter because non-Partners were assumed not to have implemented any changes that would have resulted in reduced emissions since 1999.

The regression equations are:

Non-Partner small utilities (fewer than 10,000 transmission miles, in kilograms):

$$\text{Emissions (kg)} = 0.89 \times \text{Transmission Miles}$$

Non-Partner large utilities (more than 10,000 transmission miles, in kilograms):

$$\text{Emissions (kg)} = 0.58 \times \text{Transmission Miles}$$

Data on transmission miles for each non-Partner utility for the years 2000, 2003, 2006, and 2009 were obtained from the 2001, 2004, 2007, and 2010 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010). The U.S. transmission system grew by over 25,000 miles between 2000 and 2003 and by over 52,000 miles between 2003 and 2006. These periodic increases are assumed to have occurred gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.3 percent between 2000 and 2003 and 2.6 percent between 2003 and 2006. This growth rate slowed to 0.2% from 2006 to 2009 as transmission miles increased by just 4,400 miles (approximately).

As a final step, total electric power system emissions 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) and the non-Partner emissions (determined using the 1999 regression equations).

1990 through 1998 Emissions from Electric Power Systems

Because most utilities participating in the Partnership reported emissions only for 1999 through 2010, modeling was

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[164] Partners in EPA's SF_6 Emission Reduction Partnership reduced their emissions by approximately 62% from 1999 to 2010.

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 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). [165] (Although equation 7.3 of the 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.)

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [166]

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 15.0 Tg CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1990 through 2010 Emissions from Manufacture of Electrical Equipment

The 1990 to 2010 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 2010 were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (141.1 Tg CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate

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[165] 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.

[166] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. This ratio was then multiplied by the total industry nameplate capacity estimate 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

To estimate the uncertainty associated with emissions of SF_6 from Electric Transmission and Distribution, uncertainties associated with three quantities were estimated: (1) emissions from Partners, (2) emissions from non-Partners, and (3) 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 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 5.3 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2010 from non-Partners: 1) uncertainty in the coefficients (as defined by the regression standard error estimate), and 2) the uncertainty in total transmission miles for non-Partners. In addition, there is uncertainty associated with the assumption that the emission factor used for non-Partner utilities (which accounted for approximately 57 percent of U.S. transmission miles in 2010) will remain at levels defined by Partners who reported in 1999. However, the last source of uncertainty was not modeled.

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 Tier 2 quantitative uncertainty analysis are summarized in Table 4-96. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 9.2 and 14.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 22 percent below and 25 percent above the emission estimate of 11.8 Tg CO_2 Eq.

Table 4-96: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (Tg CO_2 Eq. and percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to 2010 Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	11.8	9.2	14.7	-22%	+25%

[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, and emissions based on atmospheric measurements declined by 27 percent over the same period.

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 for 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

Recalculations Discussion

In the current Inventory, SF_6 emission estimates for the period 1990 through 2009 were updated relative to the previous report based on 1) new data from EPA's SF_6 Emission Reduction Partnership; 2) revisions to interpolated and extrapolated non-reported Partner data; and 3) a correction made to 1999 through 2001 reported emissions data for a Partner. Correcting the reported emissions not only directly impacted overall emissions for 1999 through 2001, but also impacted the regression coefficient used to estimate emissions for non-Partners, which is based on the relationship between transmission miles and emissions for Partners that reported emissions in 1999. Specifically, the regression coefficient for utilities with fewer than 10,000 transmission miles decreased from 1.001 kg of emissions per transmission mile to 0.89 kg of emissions per transmission mile. Based on the revisions listed above, SF_6 emissions from electrical transmission and distribution decreased between 6 and 9 percent for each year from 1990 through 2009 relative to the previous report.

4.24. Industrial Sources of Indirect Greenhouse Gases- To Be Updated

In addition to the main greenhouse gases addressed above, many industrial processes 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 non-energy industrial processes from 1990 to 2009 are reported in Table 4-97.

Table 4-97: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007	2008	2009
NO_x	**591**	**607**	**626**	**569**	**553**	**537**	**520**	**568**
Other Industrial Processes	343	362	435	437	418	398	379	436
Chemical & Allied Product Manufacturing	152	143	95	55	57	59	61	55
Metals Processing	88	89	81	60	61	62	62	60
Storage and Transport	3	5	14	15	15	16	16	15
Miscellaneous*	5	8	2	2	2	2	2	2
CO	**4,125**	**3,959**	**2,216**	**1,555**	**1,597**	**1,640**	**1,682**	**1,549**
Metals Processing	2,395	2,159	1,175	752	788	824	859	752
Other Industrial Processes	487	566	537	484	474	464	454	484
Chemical & Allied Product Manufacturing	1,073	1,110	327	189	206	223	240	187
Storage and Transport	69	23	153	97	100	103	104	97
Miscellaneous*	101	102	23	32	30	27	25	29
NMVOCs	**2,422**	**2,642**	**1,773**	**1,997**	**1,933**	**1,869**	**1,804**	**1,322**
Storage and Transport	1,352	1,499	1,067	1,308	1,266	1,224	1,182	662
Other Industrial Processes	364	408	412	415	398	383	367	395
Chemical & Allied Product Manufacturing	575	599	230	213	211	210	207	206
Metals Processing	111	113	61	44	44	43	42	44
Miscellaneous*	20	23	3	17	14	10	7	15

* 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.

Note: Totals may not sum due to independent rounding.

Methodology

These emission estimates were obtained from preliminary data (EPA 2010, EPA 2009), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. 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 categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

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 2008. Details on the emission trends through time are described in more detail in the Methodology section, above.

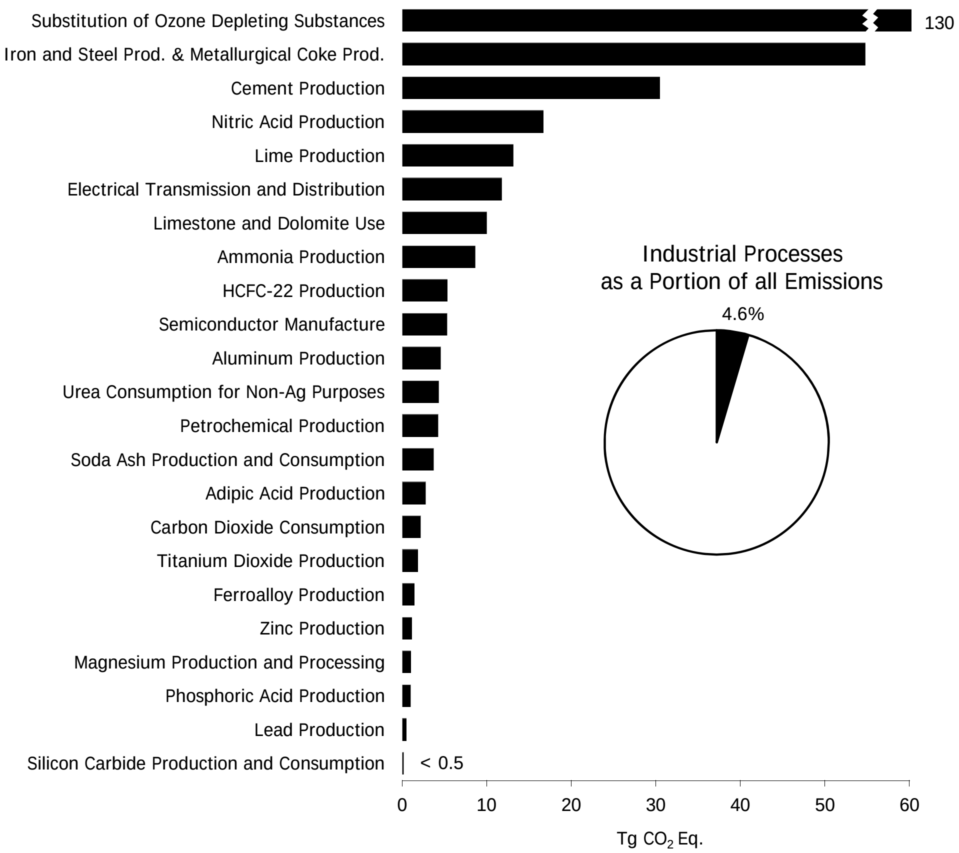

Figure 4-1: 2010 Industrial Processes Chapter Greenhouse Gas Sources

5. Solvent and Other Product Use

Greenhouse gas emissions are produced as a by-product of various solvent and other product uses. In the United States, emissions from Nitrous Oxide (N_2O) Product Uses, the only source of greenhouse gas emissions from this sector, accounted for less than 0.1 percent of total U.S. anthropogenic greenhouse gas emissions on a CO_2 equivalent basis in 2010 (see Table 5-1). Indirect greenhouse gas emissions also result from solvent and other product use, and are presented in Table 5-5 in gigagrams (Gg).

Table 5-1: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq. and Gg)

Gas/Source	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
N_2O from Product Uses								
Tg CO_2 Eq.	4.4		4.4	4.4	4.4	4.4	4.4	4.4
Gg	14		14	14	14	14	14	14

5.1. *Nitrous Oxide from Product Uses (IPCC Source Category 3D)*

N_2O is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor. Two companies operate a total of five N_2O production facilities in the United States (Airgas 2007; FTC 2001). 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. As such, it is used to treat short-term pain, for sedation in minor elective surgeries, and as an induction anesthetic. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2010 was approximately 15 Gg (Table 5-2).

Table 5-2: N_2O Production (Gg)

Year	**Gg**
1990	16
2005	15
2006	15
2007	15
2008	15
2009	15
2010	15

N_2O emissions were 4.4 Tg CO_2 Eq. (14 Gg) in 2010 (Table 5-3). 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 5-3: N_2O Emissions from N_2O Product Usage (Tg CO_2 Eq. and Gg)

Year	**Tg CO_2 Eq.**	**Gg**

1990	4.4	14
2005	4.4	14
2006	4.4	14
2007	4.4	14
2008	4.4	14
2009	4.4	14
2010	4.4	14

Methodology

Emissions from N_2O product usage were calculated by first multiplying the total amount of N_2O produced in the United States by the share of the total quantity of N_2O attributed to each end use. This value was then multiplied by the associated emission rate for each end use. After the emissions were calculated for each end use, they were added together to obtain a total estimate of N_2O product usage emissions. Emissions were determined using the following equation:

$$N_2O \text{ Product Usage Emissions} = \sum i \text{ [Total U.S. Production of } N_2O] \times \text{[Share of Total Quantity of } N_2O \text{ Usage by Sector i]} \times \text{[Emissions Rate for Sector i]}$$

where,

i = Sector.

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 2010, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other 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 unavailable data, production estimates for years 2004 through 2010 were held 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 unavailable data, the share of total quantity of N_2O usage data for years 2004 through 2010 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 2010 N_2O emission estimate from N_2O product usage was calculated using the IPCC Guidelines for National Greenhouse Gas Inventories (2006) Tier 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 Tier 2 quantitative uncertainty analysis are summarized in Table 5-4. N_2O emissions from N_2O product usage were estimated to be between 4.1 and 4.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the emissions estimate of 4.4 Tg CO_2 Eq.

Table 5-4: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a]**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
N_2O Product Usage	N_2O	4.4	4.1	4.7	-8%	+8%

[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 2010. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

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.

5.2. Indirect Greenhouse Gas Emissions from Solvent Use – TO BE UPDATED

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., indirect greenhouse gases).[167] 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 solvents. As some of

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[167] Solvent 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 the Industrial Processes chapter.

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. In the United States, emissions from solvents are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The evaporation process varies depending on different solvent uses and solvent types. The major categories of solvent uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (i.e., electronics, etc.), dry cleaning, and non-industrial uses (i.e., uses of paint thinner, etc.).

Total emissions of NO_x, NMVOCs, and CO from 1990 to 2009 are reported in Table 5-5.

Table 5-5: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**
NO_x	**1**	**3**	**3**	**4**	**4**	**4**	**3**
Surface Coating	1	3	3	4	4	4	3
Graphic Arts	+	+	+	+	+	+	+
Degreasing	+	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	+	+	+
Other Industrial Processes[a]	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+
Other	NA	+	+	+	+	+	+
CO	**5**	**45**	**2**	**2**	**2**	**2**	**2**
Surface Coating	+	45	2	2	2	2	2
Other Industrial Processes[a]	4	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	+	+	+
Degreasing	+	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+	+
Other	NA	+	+	+	+	+	+
NMVOCs	**5,216**	**4,384**	**3,851**	**3,846**	**3,839**	**3,834**	**2,583**
Surface Coating	2,289	1,766	1,578	1,575	1,573	1,571	1,058
Non-Industrial Processes[b]	1,724	1,676	1,446	1,444	1,441	1,439	970
Degreasing	675	316	280	280	280	279	188
Dry Cleaning	195	265	230	230	229	229	154
Graphic Arts	249	222	194	193	193	193	130
Other Industrial Processes[a]	85	98	88	88	87	87	59
Other	+	40	36	36	36	36	24

[a] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[b] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 Gg.

Methodology

Emissions were calculated by aggregating solvent use data based on information relating to solvent 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 solvent-specific emission factors to the amount of solvents used for surface coatings, an estimate of emissions was obtained. Emissions of CO and NO_x result primarily from thermal and catalytic incineration of solvent-laden gas streams from painting booths, printing operations, and oven exhaust.

These emission estimates were obtained from preliminary data (EPA 2010, EPA 2009), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of solvent purchased) 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 the reliability of correlations between activity data and actual emissions.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2009. Details on the emission trends through time are described in more detail in the Methodology section, above.

6. 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 6-1). 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 6-1: 2010 Agriculture Chapter Greenhouse Gas Emission Sources

In 2010, the Agriculture sector was responsible for emissions of 444.4 teragrams of CO_2 equivalents (Tg CO_2 Eq.), or 6.5 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 about 21 percent and 8 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 69 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 6-1 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2010, CH_4 emissions from agricultural activities increased by 16.9 percent, while N_2O emissions fluctuated from year to year, but overall increased by 10.2 percent.

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**172.9**	**193.9**	**195.9**	**202.9**	**202.6**	**200.8**	**202.2**
Enteric Fermentation	133.8	139.0	141.4	143.8	143.4	142.6	141.3
Manure Management	31.7	47.9	48.4	52.7	51.8	50.7	52.0
Rice Cultivation	7.1	6.8	5.9	6.2	7.2	7.3	8.6
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**226.5**	**245.3**	**245.1**	**245.8**	**248.0**	**242.9**	**242.3**
Agricultural Soil Management	211.7	227.7	226.6	227.2	229.7	224.6	223.8
Manure Management	14.8	17.6	18.4	18.5	18.3	18.2	18.3
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**399.4**	**439.2**	**440.9**	**448.7**	**450.6**	**443.7**	**444.4**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**8,234**	**9,232**	**9,327**	**9,663**	**9,647**	**9,564**	**9,627**
Enteric Fermentation	6,373	6,618	6,731	6,850	6,829	6,788	6,728
Manure Management	1,511	2,280	2,303	2,508	2,465	2,416	2,478
Rice Cultivation	339	326	282	295	343	349	410
Field Burning of Agricultural Residues	10	8	11	11	11	11	11
N_2O	**731**	**791**	**791**	**793**	**800**	**784**	**781**
Agricultural Soil Management	683	734	731	733	741	725	722
Manure Management	48	57	59	60	59	59	59

Field Burning of Agricultural Residues	+	+	+	+	+	+	+

+ Less than 0.5 Gg.

Note: Totals may not sum due to independent rounding.

6.1. Enteric Fermentation (IPCC Source Category 4A)

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 among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules) 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 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, 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 6-3 and Table 6-4.

Total livestock CH_4 emissions in 2010 were 141.3 Tg CO_2 Eq. (6,728 Gg). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 72 percent in 2010. Emissions from dairy cattle in 2010 accounted for 23 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules, burros, and donkeys.

From 1990 to 2010, emissions from enteric fermentation have increased by 5.6 percent. Generally, emissions decreased from 1996 to 2003, though with a slight increase in 2002. This trend was mainly due to decreasing populations of both beef and dairy cattle and increased digestibility of feed for feedlot cattle. Emissions increased from 2004 through 2007, as both dairy and beef populations have undergone increases and the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again in 2008 to 2010 as beef cattle populations again decreased. During the timeframe of this analysis, populations of sheep have decreased 51 percent while horse populations have increased over 87 percent, mostly between 2001 and 2006. Goat and swine populations have increased 25 percent and 20 percent, respectively, during this timeframe, though with slight decreases from 2009 to 2010, while the populations of American bison and mules, burros, and donkeys have more than quadrupled.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Beef Cattle	96.2	101.4	103.0	104.0	103.1	102.0	101.1
Dairy Cattle	31.8	30.4	31.1	32.4	32.9	33.2	33.0
Horses	1.9	3.5	3.6	3.6	3.6	3.6	3.6
Swine	1.7	1.9	1.0	2.1	2.1	2.1	2.0
Sheep	1.9	1.0	1.9	1.0	1.0	1.0	0.9
Goats	0.3	0.3	0.3	0.3	0.3	0.3	0.3
American Bison	0.1	0.4	0.4	0.3	0.4	0.3	0.3
Mules, Burros, and Donkeys	+	+	0.1	0.1	0.1	0.1	0.1
Total	**133.8**	**139.0**	**141.4**	**143.8**	**143.4**	**142.6**	**141.3**

Notes: + Does not exceed 0.05 Tg CO2 Eq. Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	2005	2006	2007	2008	2009	2010
Beef Cattle	4,581	4,829	4,904	4,953	4,909	4,857	4,812
Dairy Cattle	1,513	1,449	1,479	1,544	1,564	1,581	1,569
Horses	91	166	171	171	171	171	171
Swine	81	92	93	98	101	99	97
Sheep	91	49	50	49	48	46	45
Goats	13	14	15	16	16	16	16
American Bison	4	17	17	16	17	17	16
Mules, Burros, and Donkeys	1	2	2	3	3	3	3
Total	**6,373**	**6,618**	**6,731**	**6,850**	**6,829**	**6,788**	**6,728**

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, burrow, and donkeys) 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 Steers)
    - 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 3.9. 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 2011).

Diet characteristics were estimated by region for U.S. dairy, foraging beef, and feedlot beef cattle. These estimates 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 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 1990-2009. 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, 1999-2002, 2003, 2004-2006, 2007, and 2008 onwards. 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 Dr. Shawn Archibeque (2011), based on diet information in USDA (2010). Weight and weight gains for cattle were estimated from Holstein Association USA (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 3.9 for more details on the method used to characterize cattle diets and weights in the United States.

To estimate CH_4 emissions from all cattle types except calves younger than 7 months,[168] 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, and bulls), 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, 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, and bulls. To estimate emissions from cattle, population data from the transition matrix were multiplied by the calculated emission factor for each cattle type. More details are provided in Annex 3.9.

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 2010. Also, 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 and swine were obtained for all years from USDA NASS (USDA 2011). Horse population data were obtained from the Food and Agriculture Organization of the United Nations (FAO) FAOSTAT database (FAO 2011), because USDA does not estimate U.S. horse populations annually. Goat and mule, burro, and donkey population data were available for 1987, 1992, 1997, 2002, and 2007 (USDA 1992, 1997, 2011); the remaining years between 1990 and 2010 were interpolated and extrapolated from the available estimates. American bison population estimates were available from USDA for 2002 and 2007 (USDA 2011) 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

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[168] Because calves younger than 7 months consume mainly milk and the IPCC recommends the use of a methane conversion factor of zero for all juveniles consuming only milk, this results in no methane emissions from this subcategory of cattle.

points, and ratios of population to slaughter statistics (USDA 2011), as described in more detail in Annex 3.9. Methane emissions from sheep, goats, swine, horses, American bison, and mules, burros, and donkeys 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 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 3.9 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 Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory report. There have been no significant changes to the methodology, although the source of some input variables have been updated, at this time there are not better estimates available for the uncertainty ranges around the 2010 activity data and emission factor input variables used in the current submission. Consequently, these uncertainty estimates were directly applied to the 2010 emission estimates.

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 6-5. Based on this analysis, enteric fermentation CH_4 emissions in 2010 were estimated to be between 125.8 and 166.7 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2010 emission estimate of 141.3 Tg 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 inventory emission estimates. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates because there is a higher degree of uncertainty among the FAO population estimates used for horses than for the USDA population estimates used for swine, goats, and sheep. American bison, mules, burros, and donkeys were excluded from the initial uncertainty estimate because they were not included in the estimate of emissions at that time, although because of their small populations they would not significantly increase the uncertainty estimate ranges of the overall emissions from enteric fermentation.

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate**[a, b, c]			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Enteric Fermentation	CH_4	141.3	125.8	166.7	-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 submitted in 2003 and applied to the 2010 estimates.

c The overall uncertainty calculated in 2003, and applied to this inventory, did not include uncertainty estimates for American bison, mules, burros, and donkeys, and was based on the Tier 1 methodology for bulls. Consequently, there was more uncertainty with bull emissions than with other cattle types.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. 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. Recent updates to the foraging portion of the diet values for cattle 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 submission 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 (N) 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

There were several modifications to the estimates relative to the previous Inventory that had an effect on emission estimates, including the following:

- The previous Inventory report, for 1990 through 2009, estimated emissions from bulls using Tier 1 methods, while the rest of the cattle population was estimated using Tier 2. The current Inventory now applies Tier 2 methods to estimate emissions from bulls for each year. This resulted in an increase of emissions from bulls by an average of approximately 79 percent per year compared to the previous Inventory estimates, such that bulls represent 3.4 percent of total enteric fermentation emissions from cattle.

- Revisions to the DE values for foraging cattle diets were applied to all years covered by this inventory, resulting in an average change of less than 0.1 percent for foraging beef cattle emissions estimates for 1990 through 2006 and an average increase of 0.4 percent for 2007 through 2009. Details on the current dietary assumptions are discussed in Annex 3.9.

- During the QA/QC process, it was realized that the one data point from 1988 (total births) had been revised by USDA since its original download. Therefore, the data point was corrected from 39,318.0 to 39,317.9 thousand births. This is a very minor change, but it is noted in detail specifically because it affects 1990 base year emissions by trickling through the transition matrix in the growing populations for 1989 and 1990.

- The equations used to distribute end-of-year remaining populations for feedlot cattle to the individual state populations were updated so that the population proportions reflect the current year rather than the following year populations. This did not affect total populations, but there were minor changes to the populations by state for feedlot cattle for all years.

- Previously, American bison and mules, burros, and donkeys were excluded from this source category. Emission estimates are now included for these animal types for all years, and contribute an average of 0.2 percent of total emissions from enteric fermentation across the time series.

- The USDA published revised estimates in several categories that affected historical emissions estimated for cattle, including slight revisions in 2009 cattle on feed population estimates for "other states" (aggregated data for states with small populations of cattle on feed), dairy cow milk production for several states, and steer and heifer placement and slaughter statistics. Additionally, calf births were revised for both the 2008 and 2009 estimates. These changes had an insignificant impact on the overall results.

- There were additional population changes for goats from 2003 through 2006, sheep for 2004, 2006, and 2009, and swine in 2009, as discussed in the recalculations discussion for manure management. Historical emission estimates for goats increased an average of 12.1 percent per year compared to the previous inventory estimates for the years mentioned above. All other population changes resulted in a decrease in emissions of less than 1 percent for the animal type and year noted.

As a result of these changes, overall methane emissions from enteric fermentation increased an average of 111 Gg (1.7 percent) per year for 1990 through 2009.

Planned Improvements

Continued research and regular updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. Ongoing revisions 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;
- Given the many challenges in characterizing dairy diets, further investigation will be conducted on additional sources or methodologies for estimating DE for dairy. For example, the current method causes some significant shifts in data between years that may not mimic actual feeding conditions. Regional trend lines may be used to smooth the transition.
- The possible breakout of other animal types (i.e., sheep, swine, goats, horses) from national estimates to state-level estimates or updating to Tier 2 methodology; and
- The investigation of methodologies for including enteric fermentation emission estimates from poultry.

In addition, 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.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. 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.[169] Indirect N_2O emissions are produced as result of the volatilization of N as NH_3 and NO_x and runoff and leaching of N during treatment, storage and transportation.

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 materials 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 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)

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[169] 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.

(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 does not include any leaching losses.

Estimates of CH_4 emissions in 2010 were 52.0 Tg CO_2 Eq. (2,478 Gg), 64 percent higher than in 1990. Emissions increased on average by 1.0 Tg CO_2 Eq. (3.0 percent) annually over this period. The majority of this increase was from swine and dairy cow manure, where emissions increased 20 and 107 percent, respectively. Although the majority of 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 limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site. Although national dairy animal populations have been generally decreasing, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country. 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 facilities is translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This shift 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 2009a). Methane emissions from sheep have decreased significantly since 1990 (a 56 percent decrease from 1990 to 2010); however, this is mainly due to population changes. Overall, sheep contribute less than one percent of CH_4 emissions from animal manure management. From 2009 to 2010, there was a 2.6 percent increase in total CH_4 emissions, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

In 2010, total N_2O emissions were estimated to be 18.3 Tg CO_2 Eq. (59 Gg); in 1990, emissions were 14.8 Tg CO_2 Eq. (48 Gg). 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 24 percent increase from 1990 to 2010 and a less than 1 percent increase from 2009 through 2010.

Table 6-6 and Table 6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990	2005	2006	2007	2008	2009	2010
CH_4[a]	**31.7**	**47.9**	**48.4**	**52.7**	**51.8**	**50.7**	**52.0**
Dairy Cattle	12.6	22.4	23.1	25.7	26.0	25.9	26.0
Beef Cattle	2.7	2.8	2.9	2.9	2.8	2.7	2.8
Swine	13.1	19.2	18.9	20.6	19.7	18.8	19.9
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Poultry	2.8	2.7	2.7	2.8	2.7	2.7	2.7
Horses	0.5	0.6	0.6	0.6	0.5	0.5	0.5
N_2O[b]	**14.8**	**17.6**	**18.4**	**18.5**	**18.3**	**18.2**	**18.3**
Dairy Cattle	5.3	5.7	5.8	5.9	5.8	5.8	5.9
Beef Cattle	6.5	7.8	8.3	8.2	8.1	8.1	8.2
Swine	1.2	1.8	1.8	2.0	2.0	2.0	1.9
Sheep	0.1	0.4	0.4	0.4	0.4	0.3	0.3
Goats	+	+	+	+	+	+	+

Poultry	1.5	1.7	1.7	1.7	1.7	1.6	1.6
Horses	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Total	**46.5**	**65.5**	**66.7**	**71.1**	**70.0**	**68.9**	**70.4**

+ Less than 0.05 Tg 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.

Table 6-7: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990	2005	2006	2007	2008	2009	2010
CH_4[a]	**1,511**	**2,280**	**2,303**	**2,508**	**2,465**	**2,416**	**2,478**
Dairy Cattle	599	1069	1101	1224	1238	1233	1239
Beef Cattle	128	135	138	136	132	131	134
Swine	624	914	901	982	938	896	948
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	131	134	129	128	129
Horses	22	28	27	27	24	24	24
N_2O[b]	**48**	**57**	**59**	**60**	**59**	**59**	**59**
Dairy Cattle	17	18	19	19	19	19	19
Beef Cattle	21	25	27	27	26	26	27
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	1	1	1	1	1	1	1

+ Less than 0.5 Gg.

[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.

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 for this Inventory. See Annex 3.10 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 waste management system (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 2010 for all livestock types, except horses and goats were obtained from USDA NASS. For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the 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 6.1 and in more detail in Annex 3.9. Horse population data were obtained from the FAOSTAT database (FAO 2010). Goat population data for 1992, 1997, 2002, and 2007 were obtained from the *Census of Agriculture* (USDA 2009a).

- The TAM is an annual average weight which was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996a), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1999) and others (EPA 1992, Safley 2000, ERG 2010a). For a description of the TAM used for cattle, please see section 6.1, Enteric Fermentation.
- WMS usage was estimated for swine and dairy cattle for different farm size categories using data from USDA (USDA 1996b, 1998b, 2000a, 2009a) 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 2000b, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).
- VS production rates for all cattle except for bulls and 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 1996a, 2008 and ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998).
- 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, and 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.
- Anaerobic digestion system data were obtained from the EPA AgSTAR Program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the AgSTAR project database (EPA 2011). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).

To estimate CH_4 emissions for cattle, 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. 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 bulls and 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 1996a, 2008 and ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998).
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006).
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.1).

To estimate N_2O emissions for cattle, 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 animals other than cattle, 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 1000 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 2003) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory report 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 Tier 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 2010 emission estimates.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8. Manure management CH_4 emissions in 2010 were estimated to be between 42.7 and 62.5 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2010 emission estimate of 52.0 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 15.4 and 22.7 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2010 emission estimate of 18.3 Tg CO_2 Eq.).

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a]**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Manure Management	CH_4	52.0	42.7	62.5	-18%	+20%
Manure Management	N_2O	18.3	15.4	22.7	-16%	+24%

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

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. 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.

The U.S. specific values for TAM, Nex, VS, B_o, MCF, and the resulting implied emission factors were also compared to the IPCC default values. 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 IPPC default values. For example, the U.S. implied CH_4 emission factor for dairy cattle is significantly higher than the IPCC default implied CH_4 emission factor. This is because U.S. dairy manure is most commonly managed in liquid systems, which produce more CH_4.

Recalculations Discussion

The CEFM produces population, VS and Nex data for cattle that are used in the manure management inventory. As a result, all changes to the CEFM described in Section 6.1 Enteric Fermentation contributed to changes in the population, VS and Nex data used for calculating CH_4 and N_2O cattle emissions from manure management.

Data from the 2007 *Census of Agriculture* were incorporated into the inventory. Census farm size distribution data were used to update the WMS distributions for dairy and swine in 2007. The dairy and swine WMS distributions between 2002 and 2007 were extrapolated based on the 2002 and 2007 data; WMS distributions after 2007 were assumed to be equal to 2007 values. The dairy and swine WMS update caused changes in dairy and swine emission estimates from 2003 on.

In addition, census county-level population data were used to update the county-level population estimates. These estimates are used as input to the Agricultural Soils inventory and to determine population-weighted state temperatures which are used to calculate MCFs for liquid systems. The county-level population update caused minor changes in methane emissions for all animals from 1990 on.

State animal populations were updated to reflect updated USDA NASS datasets. Population changes occurred for all animals in 2009. Sheep populations experienced changes in 2004 to 2006 and 2008 estimates due to a change in the "other states" reported by USDA NASS.

Due to time constraints during development of previous Inventory reports, the temperature data had not been updated since 2008. For the current Inventory, temperature data were updated to incorporate the most recent available data. The temperature data are used to estimate MCFs for liquid systems; this update caused minor changes in CH_4 emission estimates from dairy, swine, beef, and poultry from 2007 on.

Planned Improvements

Tier 1 emission estimates for mules, donkeys, burros, and American bison will be incorporated into future inventories. Although these animal groups will not contribute significantly to the overall U.S. emissions from manure management, they will be included for completeness and consistency across source categories.

The uncertainty analysis will be updated in the future to more accurately assess uncertainty of emission calculations. This update is necessary due to the extensive changes in emission calculation methodology that was made in the current Inventory, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N_2O emissions.

6.3. Rice Cultivation (IPCC Source Category 4C)

Most of the world's rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes most of the oxygen present in the soil, causing anaerobic soil conditions. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (some oxygen remains at the interfaces of soil and water, and soil and root system) (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also 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 system under which rice is grown is one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce 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 are dead, so the primary CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with shallower flooding depths. Some flooded 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. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. 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 (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding, and weeding practices). The factors that determine the amount of organic material available to decompose (i.e., organic fertilizer use, soil type, rice variety,[170] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season; the total amount of CH_4 released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate and ammonium sulfate) appear to inhibit CH_4 formation.

Rice is cultivated in eight states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, Oklahoma, and Texas.[171] Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers apply organic fertilizers in the form of residue from the previous rice crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of southwest Louisiana, Texas, and Florida often allow for a second, or ratoon, rice crop. Ratoon

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[170] 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.

[171] A very small amount of rice is grown on about 20 acres in South Carolina; however, this amount was determined to be too insignificant to warrant inclusion in national emission estimates.

crops are much less common or non-existent in Arkansas, California, Mississippi, Missouri, Oklahoma, and northern areas of Louisiana. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow the stubble to decay aerobically), the amount of organic material that is available for anaerobic decomposition is considerably higher than with the first (i.e., primary) crop.

Rice cultivation is a small source of CH_4 in the United States (Table 6-9 and Table 6-10). In 2010, CH_4 emissions from rice cultivation were 8.6 Tg CO_2 Eq. (410 Gg). Annual emissions fluctuated unevenly between the years 1990 and 2010, ranging from an annual decrease of 14 percent to an annual increase of 17 percent. There was an overall decrease of 17 percent between 1990 and 2006, due to an overall decrease in primary crop area.[172] However, emission levels increased again by 45 percent between 2006 and 2010 due to an increase in rice crop area in all states except Oklahoma, which reported no rice production in 2009 and 2010. The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states.

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	2005	2006	2007	2008	2009	2010
Primary	**5.1**	**6.0**	**5.1**	**4.9**	**5.3**	**5.6**	**6.5**
Arkansas	2.1	2.9	2.5	2.4	2.5	2.6	3.2
California	0.7	0.9	0.9	1.0	0.9	1.0	1.0
Florida	+	+	+	+	+	+	+
Louisiana	1.0	0.9	0.6	0.7	0.8	0.8	1.0
Mississippi	0.4	0.5	0.3	0.3	0.4	0.4	0.5
Missouri	0.1	0.4	0.4	0.3	0.4	0.4	0.4
Oklahoma	+	+	+	+	+	+	+
Texas	0.6	0.4	0.3	0.3	0.3	0.3	0.3
Ratoon	**2.1**	**0.8**	**0.9**	**1.3**	**1.9**	**1.8**	**2.1**
Arkansas	+	+	+	+	+	+	+
Florida	+	+	+	+	+	+	+
Louisiana	1.1	0.5	0.5	0.9	1.2	1.1	1.4
Texas	0.9	0.4	0.4	0.3	0.6	0.7	0.7
Total	**7.1**	**6.8**	**5.9**	**6.2**	**7.2**	**7.3**	**8.6**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	2005	2006	2007	2008	2009	2010
Primary	**241**	**287**	**241**	**235**	**254**	**265**	**308**
Arkansas	102	139	119	113	119	125	152
California	34	45	44	45	44	47	47
Florida	1	1	1	1	1	1	1
Louisiana	46	45	29	32	39	39	45
Mississippi	21	22	16	16	19	21	26
Missouri	7	18	18	15	17	17	21
Oklahoma	+	+	+	+	+	+	+
Texas	30	17	13	12	15	14	16
Ratoon	**98**	**39**	**41**	**60**	**89**	**84**	**101**

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[172] The 14 percent decrease occurred between 2005 and 2006; the 17 percent increase happened between 1993 and 1994.

Arkansas	+	1	+	+	+	+	+
Florida	2	+	1	1	1	2	2
Louisiana	52	22	22	42	59	51	68
Texas	45	17	18	16	29	31	32
Total	**339**	**326**	**282**	**295**	**343**	**349**	**410**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

Methodology

IPCC (2006) recommends using harvested rice areas, area-based daily emission factors (i.e., amount of CH_4 emitted per day per unit harvested area), and length of growing season to estimate annual CH_4 emissions from rice cultivation. This Inventory uses the recommended methodology and employs Tier 2 U.S.-specific emission factors derived from rice field measurements. State-specific and daily emission factors were not available; however, so average U.S. seasonal emission factors were used. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This approach is consistent with IPCC (2006).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11, and the area of ratoon crop area as a percent of primary crop area is shown in Table 6-12. Primary crop areas for 1990 through 2010 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 2011). Source data for non-USDA sources of primary and ratoon harvest areas are shown in Table 6-13. California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2010 (Guethle 1999 through 2010; Lee 2003 through 2007; Mutters 2002 through 2005; Street 1999 through 2003; Walker 2005, 2007 through 2008; Buehring 2009 through 2011).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	2005	2006	2007	2008	2009	2010
Arkansas							
Primary	485,633	661,675	566,572	536,220	564,549	594,901	722,380
Ratoon[a]	-	662	6	5	6	6	7
California	159,854	212,869	211,655	215,702	209,227	225,010	223,796
Florida							
Primary	4,978	4,565	4,575	6,242	5,463	5,664	5,330
Ratoon	2,489	+	1,295	1,873	1,639	2,266	2,275
Louisiana							
Primary	220,558	212,465	139,620	152,975	187,778	187,778	216,512
Ratoon	66,168	27,620	27,924	53,541	75,111	65,722	86,605
Mississippi	101,174	106,435	76,487	76,487	92,675	98,341	122,622
Missouri	32,376	86,605	86,605	72,036	80,534	80,939	101,578
Oklahoma	617	271	17	+	77	+	+
Texas							
Primary	142,857	81,344	60,704	58,681	69,607	68,798	76,083
Ratoon	57,143	21,963	23,675	21,125	36,892	39,903	41,085
Total Primary	**1,148,047**	**1,366,228**	**1,146,235**	**1,118,343**	**1,209,911**	**1,261,431**	**1,468,300**
Total Ratoon	**125,799**	**50,245**	**52,899**	**76,544**	**113,648**	**107,897**	**129,971**
Total	**1,273,847**	**1,416,473**	**1,199,135**	**1,194,887**	**1,323,559**	**1,369,328**	**1,598,271**

[a] Arkansas ratooning occurred only in 1998, 1999, and 2005 through 2010.

+ Emissions are less than 0.1 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-12: Ratooned Area as Percent of Primary Growth Area

State	1990		1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Arkansas	0%			+	+	0%					0.1%	+	+	+	+	+
Florida	50%				65%	41%	60%	54%	100%	77%	0%	28%	30%	30%	40%	43%
Louisiana	30%					40%	30%	15%	35%	30%	13%	20%	35%	40%	35%	40%
Texas	40%					50%	40%	37%	38%	35%	27%	39%	36%	53%	58%	54%

+ Indicates ratooning rate less than 0.1 percent.

Table 6-13: Non-USDA Data Sources for Rice Harvest Information

State/Crop	1990		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Arkansas													
Ratoon	Wilson (2002 – 2007, 2009 – 2011)												
Florida													
Primary	Scheuneman (1999 – 2001)			Deren (2002)	Kirstein (2003, 2006)			Gonzales (2006 – 2011)					
Ratoon	Scheuneman (1999)			Deren (2002)	Kirstein (2003-2004)		Cantens (2005)	Gonzales (2006 – 2011)					
Louisiana													
Ratoon	Bollich (2000)		Linscombe (1999, 2001 – 2011)										
Oklahoma													
Primary	Lee (2003-2007)										Anderson (2008 – 2011)		
Texas													
Ratoon	Klosterboer (1999 – 2003)					Stansel (2004 – 2005)		Texas Ag Experiment Station (2006 – 2011)					

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 nonrepresentative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation), as well as experiments in which measurements were not made over an entire flooding season or floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results[173] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with added synthetic and organic fertilizer (Bossio et al. 1999; Cicerone et al. 1992; Sass et al. 1991a, 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

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,

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[173] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the aforementioned reasons. In addition, one measurement from the ratooned fields (i.e., the flux of 1,490 kg CH_4/hectare-season in Lindau and Bollich 1993) was excluded, because this emission rate is unusually high compared to other flux measurements in the United States, as well as IPCC (2006) default emission factors.

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 22 to 479 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. The uncertainty distributions around the primary and ratoon emission factors were derived using the distributions of the relevant primary or ratoon emission factors available in the literature and described above. Variability about the rice emission factor means was not normally distributed for either primary or ratooned crops, but rather skewed, with a tail trailing to the right of the mean. A lognormal statistical distribution was, therefore, applied in the Tier 2 Monte Carlo analysis.

Other sources of uncertainty include the primary rice-cropped area for each state, percent of rice-cropped area that is ratooned, 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. No uncertainty estimates were calculated for the practice of flooding outside of the normal rice season 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 (Tier 2) uncertainty analysis was performed using the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-14. Rice cultivation CH_4 emissions in 2010 were estimated to be between 3.0 and 21.8 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 65 percent below to 153 percent above the actual 2010 emission estimate of 8.6 Tg CO_2 Eq.

Table 6-14: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate**[a]			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Rice Cultivation	CH_4	8.6	3.0	21.8	-65%	+153%

[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 2010. 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.

Planned Improvements

A possible future improvement is to create region-specific emission factors for rice cultivation. The current methodology uses a nationwide average emission factor, derived from several studies done in a number of states. The prospective improvement would take the same studies and average them by region, presumably resulting in more spatially specific emission factors.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[174] A number of agricultural activities increase mineral N availability in soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities increase soil mineral N either directly or indirectly (see Figure 6-2). Direct increases occur through a variety of management practices that add or lead to greater release of mineral N to the soil, 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 and cultivation of organic cropland soils (i.e., soils with a high organic matter content, otherwise known as Histosols).[175] Other agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization in soils and thereby affect direct emissions. Mineral N is also made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere,[176] and these processes are influenced by agricultural management through impacts on moisture and temperature regimes in soils. These additional sources of mineral N are included at the recommendation of IPCC (2006) for complete accounting of management impacts on greenhouse gas emissions, as discussed in the Methodology section. Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N,[177] and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water. Direct emissions from agricultural lands (i.e., cropland and grassland) are included in this section, while direct emissions from forest lands and settlements are presented in the Land Use, Land-Use Change, and Forestry chapter. However, indirect N_2O emissions from all land-uses (cropland, grassland, forest lands, and settlements) are reported in this section.

Figure 6-2: Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2010 were 223.8 Tg CO_2 Eq. (722 Gg N_2O) (see Table 6-15 and Table 6-16). Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2010, although overall emissions were 5.7 percent higher in 2010 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. On average, cropland accounted for approximately 73 percent of total direct emissions, while grassland accounted for approximately 27 percent. These percentages are about the same for indirect emissions since forest lands and settlements account for such a small percentage of total indirect emissions. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 6-17 and Table 6-18.

Table 6-15: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Direct	**159.1**	**175.6**	**172.5**	**174.5**	**175.9**	**170.9**	**169.9**
Cropland	111.0	128.9	126.9	128.6	129.4	123.6	123.6
Grassland	48.0	46.8	45.5	45.9	46.5	47.4	46.3

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[174] 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).

[175] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

[176] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[177] 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.

Indirect (All Land-Use Types)	**52.6**	**52.0**	**54.1**	**52.7**	**53.7**	**53.7**	54.0
Cropland	43.1	43.6	45.9	44.5	44.7	44.9	44.9
Grassland	9.1	7.6	7.4	7.5	8.3	8.0	8.4
Forest Land	+	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	0.3	0.6	0.6	0.6	0.6	0.6	0.5
Total	**211.7**	**227.7**	**226.8**	**227.2**	**229.7**	**224.6**	**223.8**

+ Less than 0.05 Tg CO_2 Eq.

Cropland soil estimates are based on last year's inventory due to delays in the analysis. Estimates will be updated after public review.

Table 6-16: N_2O Emissions from Agricultural Soils (Gg)

Activity	1990	2005	2006	2007	2008	2009	2010
Direct	**513**	**567**	**556**	**563**	**567**	**551**	**548**
Cropland	358	416	409	415	417	399	399
Grassland	155	151	147	148	150	153	149
Indirect (All Land-Use Types)	**170**	**168**	**175**	**170**	**173**	**173**	**174**
Cropland	139	141	148	144	144	145	145
Grassland	29	25	24	24	27	26	27
Forest Land	0	+	+	+	+	+	+
Settlements	1	2	2	2	2	2	2
Total	**683**	**734**	**731**	**733**	**741**	**725**	**722**

+ Less than 0.5 Gg N_2O

Cropland soil estimates are based on last year's inventory due to delays in the analysis. Estimates will be updated after public review.

Table 6-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (Tg CO_2 Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Cropland	**111.0**	**128.9**	**126.9**	**128.6**	**129.4**	**123.6**	**123.6**
Mineral Soils	**108.2**	**126.0**	**124.0**	**125.7**	**126.5**	**120.7**	**120.7**
Synthetic Fertilizer	37.3	46.1	44.4	44.8	45.4	44.8	44.8
Organic Amendment[b]	13.8	15.6	16.1	16.1	16.0	15.7	15.7
Residue N[a]	12.4	13.7	13.8	13.9	14.3	13.1	13.1
Mineralization and Asymbiotic Fixation	44.6	50.5	49.7	50.9	50.9	47.1	47.1
Organic Soils	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Grassland	**48.0**	**46.8**	**45.5**	**45.9**	**46.5**	**47.4**	**46.1**
Synthetic Fertilizer	1.7	1.7	1.6	1.6	1.6	1.6	1.6
PRP Manure	10.7	10.7	10.5	10.8	10.0	10.3	10.0
Managed Manure	-+	-+	-+	-+	-+	-+	-+
Sewage Sludge	0.3	0.5	0.5	0.5	0.5	0.5	0.5
Residue N[c]	1.7	1.6	1.5	1.5	1.6	1.6	1.6
Mineralization and Asymbiotic Fixation	34.8	33.6	32.5	32.7	34.1	34.6	33.8
Total	**159.1**	**175.6**	**172.5**	**174.5**	**175.9**	**170.9**	**169.6**

[a] Cropland residue N inputs include N in unharvested legumes as well as crop residue N.

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[c] Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N

Cropland soil estimates are based on last year's inventory due to delays in the analysis. Estimates will be updated after public review.

Table 6-18: Indirect N_2O Emissions from all Land-Use Types (Tg CO_2 Eq.)

Activity	1990	2005	2006	2007	2008	2009	2010
Cropland	**43.1**	**43.6**	**45.9**	**44.5**	**44.7**	**44.9**	**44.9**
Volatilization & Atm. Deposition	15.7	17.7	19.2	17.4	17.9	18.5	18.5
Surface Leaching & Run-Off	27.4	25.9	26.7	27.1	26.9	26.4	26.4
Grassland	**9.1**	**7.6**	**7.4**	**7.5**	**8.3**	**8.0**	**8.4**
Volatilization & Atm. Deposition	7.7	6.5	6.0	6.4	6.9	6.8	7.7
Surface Leaching & Run-Off	1.4	1.2	1.4	1.1	1.4	1.2	0.7
Forest Land	+	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Volatilization & Atm. Deposition	+	+	+	+	+	+	+
Surface Leaching & Run-Off	+	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	**0.3**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.5**
Volatilization & Atm. Deposition	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Surface Leaching & Run-Off	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Total	**52.6**	**52.0**	**54.1**	**52.7**	**53.7**	**53.7**	**54.0**

+ Less than 0.05 Tg CO_2 Eq.

Note: Cropland soil estimates are based on last year's inventory due to delays in the analysis. Estimates will be updated after public review.

Figure 6-3: Major Crops, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Tg CO_2 Eq./year)

Figure 6-4: Grasslands, Average Annual Direct N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Tg CO_2 Eq./year)

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Gg N/year)

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions Estimated Using the DAYCENT Model, 1990-2010 (Gg N/year)

Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide the Agricultural Soil Management source category into five components: (1) direct emissions due to N additions to cropland and grassland mineral soils, including 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 and cultivation of organic cropland soils; (4) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (5) indirect emissions from soils and water due to 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 from crop residues to indirect soil N_2O emissions; (2) adopting a revised emission factor for direct N_2O emissions to the extent that Tier 1 methods are used in the Inventory (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with the biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils based on harvest yield data to the extent that Tier 1 methods are used in the Inventory; (5) accounting for indirect as well as direct emissions from N made available via mineralization of soil organic matter and litter, in addition to asymbiotic fixation[178] (i.e., computing total emissions from managed land); (6) reporting all emissions from managed lands, largely because management affects all processes leading to soil N_2O emissions; and (7) estimating emissions associated with land use and management change which can significantly change the N mineralization rates from soil organic matter. 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. Pastures are replanted occasionally in rotation with annual crops, and this practice is represented in the inventory. However, renewal of pasture that is not rotated with annual crops occasionally is not common in the United States, and is not estimated.

In previous Inventories, attempts were made to subtract "background" emissions that would presumably occur if the lands were not managed. However, this approach is likely to be inaccurate for estimating the anthropogenic influence on soil N_2O emissions. Moreover, if background emissions could be measured or modeled based on processes unaffected by anthropogenic activity, they would be a very small portion of the total emissions, due to the high inputs of N to agricultural soils from fertilization and legume cropping. Given the recommendation from IPCC (2006) and the influence of management on all processes leading to N_2O emissions from soils in agricultural systems, the decision was made to report total emissions from managed lands for this source category. Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each component.

Direct N_2O Emissions

The methodology used to estimate direct emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches. A Tier 3 process-based model (DAYCENT) was used to estimate direct emissions from major crops on mineral (i.e., non-organic) soils; as well as most of the direct emissions from grasslands (Del Grosso et al. 2010; Ogle et al. in prep). 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 6-1 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 a consistent treatment of the processes and interactions are taken into account between C and N cycling in soils.

The Tier 3 approach was 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 and Hawaii that are included in the Tier 3 method.[179] 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 for 4 out of 5 years in the cycle (i.e., 1979-1982, 1984-1987, 1989-1992, and 1994-1997). However, the NRI program began collecting annual data in 1998, and data are currently available through 2007.

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[178] 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.

[179] 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 (non-major crops) 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.

[BEGIN BOX]

Box 6-1. 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 is likely to produce 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. 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 such legacy effects when N added to soils is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

[END BOX]

The Tier 1 IPCC (2006) methodology was used to estimate (1) direct emissions from non-major crops on mineral soils (e.g., barley, oats, vegetables, and other crops); (2) the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model (i.e., federal grasslands); and (3) direct emissions from drainage and cultivation of organic cropland soils.

Major Crop Types on 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 major crops according to the National Resources Inventory (USDA-NRCS 2009), including corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton. Major crops are grown on approximately 90 percent of total croplands in the United States. 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 250m. 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 3.11 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 (i.e., leaving residues in the field after harvest instead of burning or collecting residues); and (4) mineralization of soil organic matter and litter, in addition to asymbiotic fixation. Note that commercial organic fertilizers 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 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 3.13 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 nitrous oxide 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 6.2 and Annex 3.10.

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, retention of crop residue on N_2O emissions, and asymbiotic N fixation, but these are not model inputs. The DAYCENT simulations also accounted for the approximately 3 percent of grain 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, and Cibrowski 1996), and therefore did not contribute to soil N_2O emissions.

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 at the county level since 1989, 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, and tillage practices are included in the estimation throughout the time series. It is important to note that the time series of tillage data 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 NRI point was run 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; Ogle et al. in prep). Soil N_2O emissions and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but emissions from 2008 to 2010 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years.

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.

Non-Major Crop Types on Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology was used to estimate direct N_2O emissions for mineral cropland soils that are managed for production of non-major crop types, including barley, oats, tobacco, sugarcane, sugar beets, sunflowers, millet, rice, peanuts, and other crops that were not included in the DAYCENT simulations. Estimates of direct N_2O emissions from N applications to non-major crop types 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;[180] and (3) the retention of above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure organic amendments were not included in the DAYCENT simulations because county-level data were not available. Consequently, non-manure organic amendments, as well as additional manure that was not added to major crops in the DAYCENT simulations, were included in the Tier 1 analysis. The influence of land-use change on soil N_2O emissions from non-major crops has not been addressed in this analysis, but is a planned improvement. The following sources were used to derive activity data:

- A process-of-elimination approach was used to estimate synthetic N fertilizer additions for non-major crops, because little information exists on their fertilizer application rates. The total amount of fertilizer used on farms has been estimated by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. After subtracting the portion of fertilizer applied to major crops and grasslands (see sections on Major Crops and Grasslands for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied to non-major crops.
- Similarly, a process-of-elimination approach was used to estimate manure N additions for non-major crops, because little information exists on application rates for these crops. The amount of manure N applied to major crops and grasslands was subtracted from total manure N available for land application (see sections on Major Crops and Grasslands for information on data sources), and this difference was assumed to be applied to non-major crops.
- Non-manure, non-sewage-sludge 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 2010). Manure and sewage sludge components were subtracted from total commercial organic fertilizers to avoid double counting.
- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA 1994, 1998, 2003, 2005, 2006, 2008, 2009, 2010a), 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). Approximately 3 percent of the crop residues were burned and therefore did not contribute to soil N_2O emissions, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996).

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 from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

The IPCC (2006) Tier 1 methods were used to estimate direct N_2O emissions due to drainage and cultivation of organic soils at a state scale. State-scale estimates of the total area of drained and cultivated organic soils were obtained from the *National Resources Inventory* (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 sub-tropical climates using the climate classification from IPCC (2006). Data were available for 1982, 1992, 1997, 2002 and 2007. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and tropical regions (IPCC 2006).

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[180] Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer have been excluded to avoid double counting. The dried manure N is counted with the non-commercial manure applications, and sewage sludge is assumed to be applied only to grasslands.

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 grasslands. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grasslands that are not intensively managed, while pastures are often seeded grasslands, possibly following tree removal, which may or may not be improved with practices such as irrigation and 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), 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 section for Major Crop Types on Mineral Cropland Soils. 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 (Section 6.2) and Annex 3.10. Biological N fixation is simulated within DAYCENT and therefore was not an input to the model.

Manure N deposition from grazing animals (i.e., PRP manure) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal and federal grasslands in each county were based on the proportion of non-federal to federal grassland area (See below for more information on area data). The amount of PRP manure applied on non-federal grasslands was an input to the DAYCENT model (see Annex 3.10), and included approximately 91 percent of total PRP manure. The remainder of the PRP manure N excretions in each county was assumed to be excreted on federal grasslands (i.e., DAYCENT simulations were only conducted for non-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 7.1. Data were obtained from the U.S. Department of Agriculture *National Resources Inventory* (USDA-NRCS 2009, Nusser and Goebel 1997, http://www.ncgc.nrcs.usda.gov/products/nri/index.htm) and the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD, Vogelman et al. 2001, http://www.mrlc.gov), which were reconciled with the Forest Inventory and Analysis Data (http://fia.fs.us/tools-data/data). The area data for pastures and rangeland were aggregated to the county level to estimate non-federal and federal grassland areas.

DAYCENT simulations produced per-area estimates of N_2O emissions (g N_2O-N/m^2) for pasture and rangelands, which were multiplied by the non-federal grassland areas in each county. The county-scale N_2O emission estimates for non-federal grasslands were scaled to the 63 agricultural regions (and to the state level for mapping purposes if there was more than one region in a state), and the national estimate was calculated by summing results across all regions. Tier 1 estimates of N_2O emissions for the PRP manure N deposited on federal grasslands and applied sewage sludge N were produced by multiplying the N input by the appropriate emission factor. Tier 1 estimates for emissions from manure N were calculated at the state level and aggregated to the entire country but emission from sewage sludge N were calculated exclusively at the national scale.

Each NRI point was run 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; Ogle et al. in prep). Soil N_2O emissions and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but emissions from 2008 to 2010 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from major and non-major crops on mineral cropland 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 6-15 and Table 6-16).

Indirect N_2O Emissions

This section describes the methods used for estimating indirect soil N_2O emissions from all land-use types (i.e., croplands, grasslands, forest lands, and settlements). 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, grasslands, forest lands, and settlements.

Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N from Managed Soils

As in the direct emissions calculation, 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., major croplands and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the sections on major crops and grasslands. Nitrogen 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 non-major croplands, PRP manure N excretion on federal grasslands, sewage sludge application on grasslands). The Tier 1 method and default fractions were also used to estimate N subject to volatilization from N inputs on settlements and forest lands (see the Land Use, Land-Use Change, and Forestry chapter). 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 6-18).

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 used to produce major crops and most grasslands. 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 produce non-major crops, sewage sludge amendments on grasslands, PRP manure N excreted on federal grasslands, and N inputs on settlements and forest lands. For both the DAYCENT 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 DAYCENT 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 6-18).

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 calculated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) calculated by DAYCENT; (3) direct emissions calculated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) calculated with the IPCC (2006) Tier 1 method; and (5) indirect emissions calculated 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) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions were estimated with a simple error propagation approach (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.11.

Uncertainties from the Tier 1 and Tier 3 (i.e., DAYCENT) estimates were combined using simple error propagation (IPCC 2006).

Table 6-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2010 (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct Soil N_2O Emissions	N_2O	170.9	125.4	269.3	-27%	58%
Indirect Soil N_2O Emissions	N_2O	53.7	29.1	135.6	-46%	153%

Note: Due to lack of data, uncertainties in areas for major crops, managed manure N production, PRP manure N production, other organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.
Note: The portion of direct N_2O emissions from cropland are based on last year's inventory due to delays in the analysis. Estimates will be updated after public review.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For quality control, 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. Nitrous oxide measurement data were available for 11 sites in the United States and one in Canada, representing 30 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N_2O emissions were closer to measured values at all sites compared to the IPCC Tier 1 estimate, except for Colorado dryland cropping (Figure 6-7). 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. This is not surprising because DAYCENT accounts for site-level factors (weather, soil type) that influence N_2O emissions. Nitrate leaching data were available for three sites in the United States representing nine different combinations of fertilizer amendments. This 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 (see additional information in Annex 3.11).

Figure 6-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model

Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked, as were the program scripts that were used to run the Monte Carlo uncertainty analysis. Several errors were identified following re-organization of the calculation spreadsheets, and corrective actions have been taken. In particular, some of the links between spreadsheets were missing or needed to be modified. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach were checked and no errors were found.

Recalculations Discussion

Methodological recalculations in this year's inventory were associated with the following improvements: 1) incorporation of MODIS Enhanced Vegetation Index as to reduce uncertainties in the estimation of crop production and subsequent carbon input to the soil; 2) using the National Resources Inventory (NRI) as the basis for crop histories and land use change (USDA-NRCS 2009); 3) addition of specific tillage practices with statistics from Conservation Technology and Information Center (CTIC 2004); 4) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2010 (USDA-ERS 2011); and 5) N_2O emissions from rice cultivation were estimated with the recommended emission factor from the IPCC (2006).

Planned Improvements

An automated quality assurance/quality control system is currently under development for the Tier 3 method that is used to estimate the majority of emissions associated with this source category. Currently, quality control is conducted by manual graphing and queries to determine if values are outside of an expected range. The new system will automatically create graphs, maps and conduct range checks to improve efficiency in this important step for the inventory analysis. This development will ensure a more thorough review of the inventory results.

Another improvement is to reconcile the amount of crop residues burned with the Field Burning of Agricultural Residues source category (Section 6.5). The methodology for Field Burning of Agricultural Residues was significantly updated recently, but the new estimates of crop residues burned were not incorporated into the DAYCENT runs for the Agricultural Soil Management source. Next year the estimates will be reconciled; meanwhile the estimates presented in this section use the previous methodology for determining crop residues burned.

6.5. Field Burning of Agricultural Residues (IPCC Source Category 4F)

Farming activities produce large quantities of agricultural crop residues, and farmers use or dispose of these residues in a variety of ways. For example, agricultural residues can be left on or plowed into the field; composted and then applied to soils; landfilled; or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, supplemental animal feed, or construction material. 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.

Field burning is not a common method of agricultural residue disposal in the United States. The primary crop types whose residues are typically burned in the United States are corn, cotton, lentils, rice, soybeans, sugarcane, and wheat (McCarty 2009). In 2010, CH_4 and N_2O emissions from field burning were 0.2 Tg CO_2 Eq. (11 Gg) and 0.1 Tg. CO_2 Eq. (0.3 Gg), respectively. Annual emissions from this source over the period 1990 to 2010 have remained relatively constant, averaging approximately 0.2 Tg CO_2 Eq. (10 Gg) of CH_4 and 0.1 Tg CO_2 Eq. (0.3 Gg) of N_2O (see Table 6-20 and Table 6-21).

Table 6-20: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990	2005	2006	2007	2008	2009	2010
CH_4	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	0.1	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	**0.3**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-21: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990	2005	2006	2007	2008	2009	2010
CH_4	**10**	**8**	**11**	**11**	**11**	**11**	**11**
Corn	1	1	2	1	1	1	1
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	2	2	2	3	3	3	3
Soybeans	1	1	1	1	1	1	1
Sugarcane	1	1	2	1	1	2	1
Wheat	5	3	3	4	4	4	4
N_2O	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
CO	**206**	**166**	**223**	**226**	**224**	**226**	**228**
NO_x	**19**	**19**	**34**	**30**	**29**	**31**	**30**

+ Less than 0.5 Gg

Note: Totals may not sum due to independent rounding.

Methodology

The Tier 2 methodology used for estimating greenhouse gas emissions from field burning of agricultural residues in the United States is consistent with IPCC (2006) (for more details, see Box 6-2). In order to estimate the amounts of C and N released during burning, the following equation was used:

C or N released = Σ over all crop types and states (Area Burned ÷ Crop Area Harvested × Crop Production × Residue/Crop Ratio × Dry Matter Fraction × Burning Efficiency × Combustion Efficiency × Fraction of C or N)

where,

Area Burned = Total area of crop burned, by state
Crop Area Harvested = Total area of crop harvested, by state
Crop Production = Annual production of crop in Gg, by state
Residue/Crop Ratio = Amount of residue produced per unit of crop production, by state
Dry Matter Fraction = Amount of dry matter per unit of biomass for a crop
Fraction of C or N = Amount of C or N per unit of dry matter for a crop
Burning Efficiency = The proportion of prefire fuel biomass consumed[181]

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[181] In IPCC/UNEP/OECD/IEA (1997), the equation for C or N released contains the variable 'fraction oxidized in burning.'

Combustion Efficiency = The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively181

Crop production and area harvested were available by state and year from USDA (2010) 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 and CO, or N_2O and NO_x Emissions from Field Burning of Agricultural Residues = (C or N Released) × (Emissions Ratio for C or N) × (Conversion Factor)

where,

Emissions Ratio = g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released
Conversion Factor = 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)

[BEGIN BOX]

Box 6-2: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

This Inventory calculates emissions from Burning of Agricultural Residues 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 equation used in this Inventory varies slightly in form from the one presented in the IPCC (2006) guidelines, but both equations rely on the same underlying variables. The IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues. IPCC (2006) default factors are provided only for four crops (wheat, corn, rice, and sugarcane), while this Inventory analyzes emissions from seven crops. A comparison of the methods and factors used in (1) the current Inventory and (2) the default IPCC (2006) approach was undertaken in the 1990-2009 Inventory to determine the magnitude of the difference in overall estimates resulting from the two approaches. The IPCC (2006) approach was not used because crop-specific emission factors for N_2O were not available for all crops. In order to maintain consistency of methodology, the IPCC/UNEP/OECD/IEA (1997) approach presented in the Methodology section was used.

The IPCC (2006) default approach resulted in 12 percent higher emissions of CH_4 and 25 percent higher emissions of N_2O than the estimates in the 1990 through 2009 Inventory. 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 inventory estimates are based on U.S.-specific, crop-specific, published data.

[END BOX]

Crop production data for all crops except rice in Florida and Oklahoma were taken from USDA's QuickStats service (USDA 2011). Rice production and area data for Florida and Oklahoma, which are not collected by USDA, were estimated separately. Average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) were applied to Florida acreages (Schueneman 1999, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2011), and crop yields for Arkansas (USDA 2011) were applied to Oklahoma acreages[182] (Lee 2003 through 2006; Anderson 2008 through 2011). The production data for the crop types whose residues are burned are presented in Table 6-22. Crop weight by bushel was obtained from Murphy (1993).

This variable is equivalent to (burning efficiency × combustion efficiency).

[182] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

The fraction of crop area burned was calculated using data on area burned by crop type and state[183] from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.[184] McCarty (2010) used remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate area burned by crop. For the inventory analysis, national-level area burned data were divided by national-level crop area harvested data to estimate the percent of crop area burned by crop. The average fraction of area burned by crop across all states is shown in Table 6-23. All crop area harvested data were from USDA (2010), except for rice acreage in Florida and Oklahoma, which is not measured by USDA (Schueneman 1999, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2011; Lee 2003 through 2006; Anderson 2008 through 2011). 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 assumed to be equal to the average percent area burned from the 5 years for which data were available. This average was taken at the crop and national level. Table 6-23 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 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 datum for sugarcane is from Kinoshita (1988) and that of cotton 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 6-24. 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 and conversion factors for all gases (see Table 6-25) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-22: Agricultural Crop Production (Gg of Product)

Crop	1990	2005	2006	2007	2008	2009	2010
Corn[a]	201,534	282,263	267,503	331,177	307,142	333,011	316,165
Cotton	3,376	5,201	4,700	4,182	2,790	2,654	3,942
Lentils	40	238	147	166	109	266	393
Rice	7,114	10,132	8,843	9,033	9,272	9,972	11,027
Soybeans	52,416	83,507	87,001	72,859	80,749	91,417	90,610
Sugarcane	25,525	24,137	26,820	27,188	25,041	27,608	24,821
Wheat	74,292	57,243	49,217	55,821	68,016	60,366	60,103

[a] Corn for grain (i.e., excludes corn for silage).

Table 6-23: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2006	2007	2008	2009	2010
Corn	+	+	+	+	+	+	+
Cotton	1	1	1	1	1	1	1
Lentils	1	+	1	1	1	1	1
Rice	10	6	10	13	10	10	10
Soybeans	+	+	+	+	+	+	+
Sugarcane	32	18	47	21	32	32	32
Wheat	2	2	2	2	2	2	2

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[183] Alaska and Hawaii were excluded.

[184] 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" categories.

+ Less than 0.5 percent

Table 6-24: 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 6-25: 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

There was a major methodological change in the previous year's Inventory. This year, shortly before the chapter was due for submission for expert review, an error was discovered in the uncertainty calculation for the new methodology. An updated and corrected uncertainty analysis will be performed and included with the public review version of the Inventory, but there was not enough time to perform this analysis for the expert review. Last year's discussion and data appear below as placeholders.

Due to data and time limitations, uncertainty resulting from the fact that emissions from burning of Kentucky bluegrass and "other" residues are not included in the emissions estimates was not incorporated into the uncertainty analysis. The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-26. Methane emissions from field burning of agricultural residues in 2010 were estimated to be between 0.14 and 0.32 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 40 percent below and 42 percent above the 2010 emission estimate of 0.23 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.07 and 0.13 Tg CO_2 Eq. (or approximately 29 percent below and 31 percent above the 2010 emission estimate of 0.10 Tg CO_2 Eq.).

Table 6-26: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.23	0.14	0.32	-40%	42%
Field Burning of Agricultural Residues	N_2O	0.10	0.07	0.13	-29%	31%

[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 2010. 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 Anderson (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, the crop production data for 2009 and 2010 were updated relative to the previous report using data from USDA (2011). Rice cultivation data for Florida and Oklahoma, which are not reported by USDA, were updated for 2010 through communications with state experts. The methodology was revised to sum state-level crop area burned and state-level crop area harvested data to determine a national percentage of crop area burned. In the previous Inventory, the percentage of crop area burned was determined at the state-level and then the state percentages were averaged. This update was made to improve accuracy and accommodate uncertainty calculations. These updates resulted in an 8.6 percent decrease in sector emissions in 2009, and an average decrease in emissions of 14.2 percent from 1990 to 2009.

Planned Improvements

Attempts will be made to incorporate state-level estimates of percentage of crop area burned into the uncertainty analysis next year to make the uncertainty analysis more robust. Further investigation will be also made into inconsistent 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 exceeded 100 percent. The availability of useable area harvested and other data for bluegrass and the “other crops” category in McCarty (2010) will also be investigated, in order to try to incorporate these emissions into the Inventory.

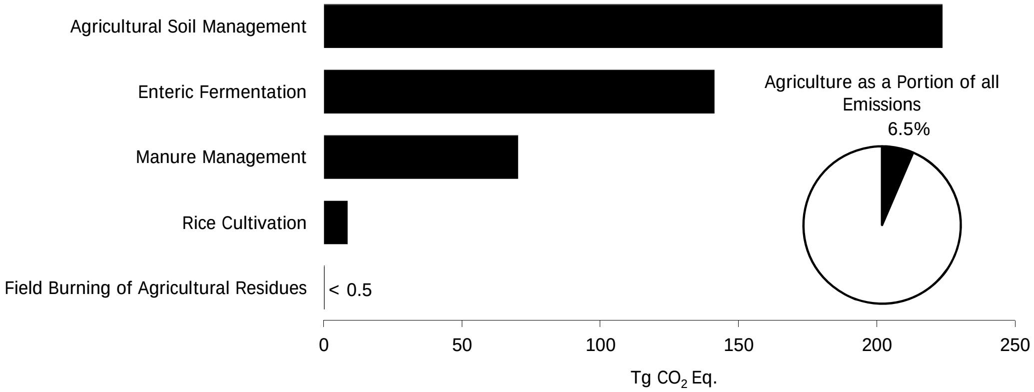
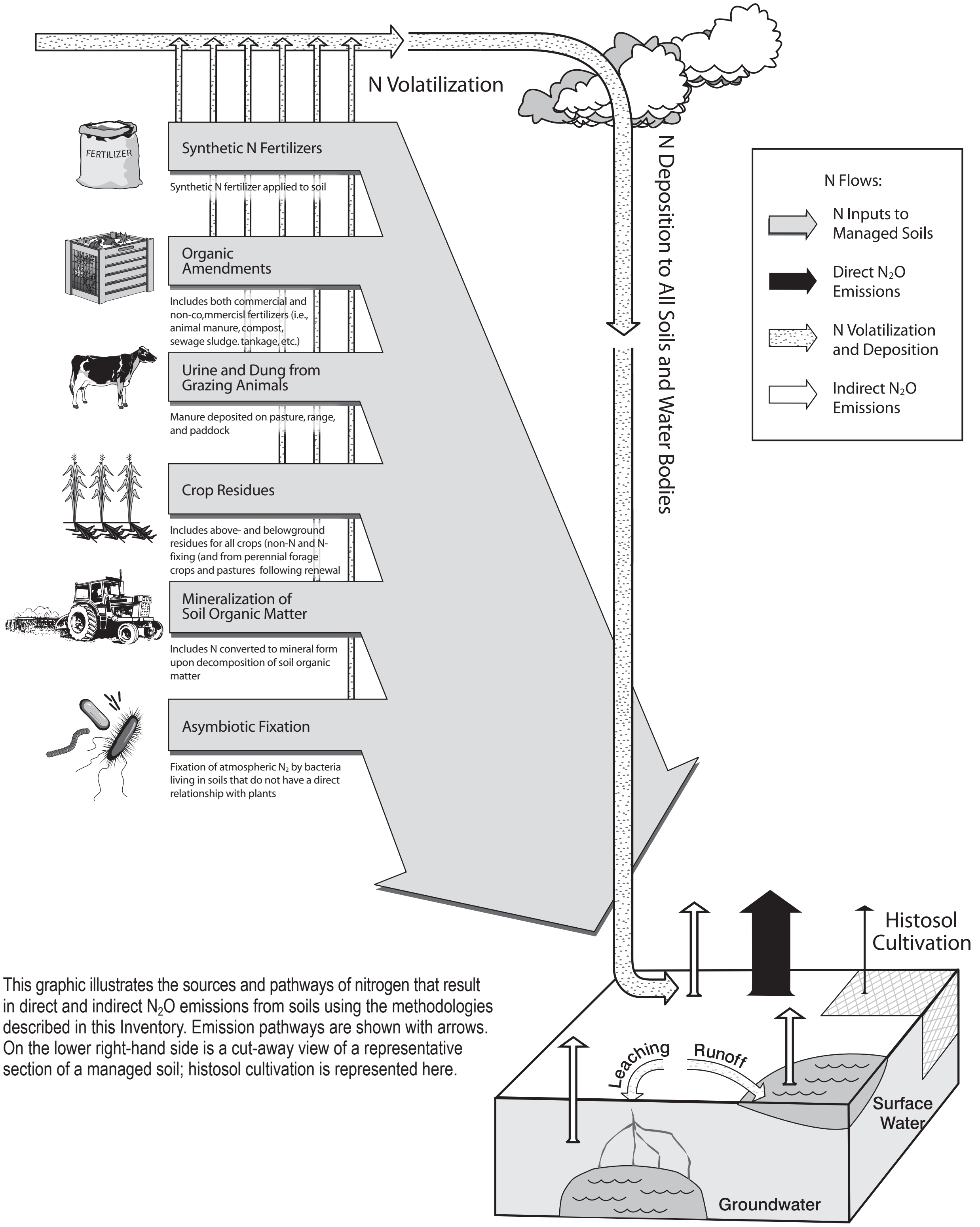


Figure 6-1: 2010 Agriculture Chapter Greenhouse Gas Sources

Figure 6-2

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.

To be provided:

Figure 6-3: Major Crops, Average Annual Direct N2O Emissions by State, Estimated Using the DAYCENT Model, 1990–2010 (Tg CO2 Eq./year)

To be provided:

Figure 6-4: Grasslands, Average Annual Direct N2O Emissions by State, Estimated Using the DAYCENT Model, 1990–2010 (Tg CO2 Eq./ year)

To be provided:

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N2O Emissions by State, Estimated Using the DAYCENT Model, 1990–2010 (Gg N/year)

To be provided:

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N2O Emissions by State, Estimated Using the DAYCENT Model,, 1990–2010 (Gg N/year)

To be provided:

Figure 6-7: Comparison of Measured Emissions at Field Sites with Modeled Emissions using the DAYCENT Simulation Model

7. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux[185] resulting from the uses and changes in land types and forests in the United States. 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, and settlements (as well as wetlands). The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest carbon (C) stocks, non-carbon dioxide (CO_2) emissions from forest fires, and the application of synthetic fertilizers to forest soils. The greenhouse gas flux reported in this chapter from agricultural lands (i.e., cropland and grassland) 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 fluxes from 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 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 1 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, periodic solid waste survey data were interpolated 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 2010 resulted in a net C sequestration of 1042.5Tg CO_2 Eq. (276.8 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 15.2 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net C sequestration[186] increased by approximately 28.8 percent between 1990 and 2010. This increase was primarily due to an increase in the rate of net C accumulation in forest C stocks. 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* increased between 1990 and 2010.

Table 7-1: Net CO_2 Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Forest Land Remaining Forest Land[1]	(701.4)	(940.9)	(963.5)	(959.2)	(938.3)	(910.6)	(921.8)
Cropland Remaining Cropland	(35.4)	(18.9)	(19.8)	(20.3)	(18.7)	(18.1)	(16.3)
Land Converted to Cropland	34.3	20.1	20.3	20.0	20.0	20.0	20.0
Grassland Remaining Grassland	(19.7)	(18.0)	(42.2)	(2.9)	(2.8)	(2.6)	(2.4)
Land Converted to Grassland	(6.3)	(11.7)	(12.2)	(10.9)	(10.8)	(10.7)	(10.7)
Settlements Remaining Settlements[2]	(57.1)	(87.8)	(89.8)	(91.9)	(93.9)	(95.9)	(98.0)
Other (Landfilled Yard Trimmings and Food Scraps)	(24.2)	(11.6)	(11.0)	(10.9)	(10.9)	(12.7)	(13.3)
Total	**(809.7)**	**(1068.8)**	**(1118.2)**	**(1076.2)**	**(1055.5)**	**(1030.7)**	**(1042.5)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

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

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[185] The term "flux" is used here to encompass both emissions of greenhouse gases to the atmosphere, and removal of C from the atmosphere. Removal of C from the atmosphere is also referred to as "carbon sequestration."

[186] 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. This is also referred to as net C sequestration.

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

Table 7-2: Net CO_2 Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry (Tg C)

Sink Category	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Forest Land Remaining Forest Land[1]	(191.3)	(256.6)	(262.8)	(261.6)	(255.9)	(248.3)	(251.4)
Cropland Remaining Cropland	(9.7)	(5.2)	(5.4)	(5.5)	(5.1)	(4.9)	(4.4)
Land Converted to Cropland	9.4	5.5	5.5	5.4	5.4	5.4	5.4
Grassland Remaining Grassland	(5.4)	(4.9)	(11.5)	(0.8)	(0.8)	(0.7)	(0.7)
Land Converted to Grassland	(1.7)	(3.2)	(3.3)	(3.0)	(3.0)	(2.9)	(2.9)
Settlements Remaining Settlements[2]	(15.6)	(23.9)	(24.5)	(25.1)	(25.6)	(26.2)	(26.7)
Other (Landfilled Yard Trimmings and Food Scraps)	(6.6)	(3.2)	(3.0)	(3.0)	(3.0)	(3.5)	(3.6)
Total	**(220.8)**	**(291.5)**	**(305.0)**	**(293.5)**	**(287.9)**	**(281.1)**	**(284.3)**

Note: 1 Tg C = 1 teragram C = 1 million metric tons C. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

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

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

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table 7-3 and Table 7-4. Liming of agricultural soils and urea fertilization in 2010 resulted in CO_2 emissions of 3.9 Tg CO_2 Eq. (3,906 Gg) and 3.5 Tg CO_2 Eq. (3,480 Gg), respectively. Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO_2 emissions of 1.0 Tg CO_2 Eq. (983 Gg), and nitrous oxide (N_2O) emissions of less than 0.05 Tg CO_2 Eq. The application of synthetic fertilizers to forest soils in 2010 resulted in direct N_2O emissions of 0.4 Tg CO_2 Eq. (1 Gg). Direct 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, direct N_2O emissions from fertilizer application to settlement soils in 2010 accounted for 1.5 Tg CO_2 Eq. (5 Gg). This represents an increase of 50 percent since 1990. Forest fires in 2010 resulted in methane (CH_4) emissions of 4.8Tg CO_2 Eq. (231 Gg), and in N_2O emissions of 4.0 Tg CO_2 Eq. (13 Gg).

Table 7-3: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Source Category	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CO_2	**8.1**	**8.9**	**8.8**	**9.2**	**9.6**	**8.2**	**8.4**
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.3	4.2	4.5	5.0	3.7	3.9
Urea Fertilization	2.4	3.5	3.7	3.8	3.6	3.5	3.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.1	0.9	1.0	1.0	1.1	1.0
CH_4	**2.5**	**8.1**	**17.9**	**14.6**	**8.8**	**5.8**	**4.8**
Forest Land Remaining Forest Land: Forest Fires	2.5	8.1	17.9	14.6	8.8	5.8	4.8
N_2O	**3.1**	**8.5**	**16.5**	**13.8**	**9.0**	**6.5**	**5.8**
Forest Land Remaining Forest Land: Forest Fires	2.1	6.6	14.6	11.9	7.2	4.7	4.0
Forest Land Remaining Forest Land: Forest Soils[1]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Settlements Remaining Settlements: Settlement Soils[2]	1.0	1.5	1.5	1.6	1.5	1.4	1.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total	**13.8**	**25.6**	**43.2**	**37.6**	**27.4**	**20.5**	**19.0**

+ Less than 0.05 Tg CO_2 Eq.

Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in the Agriculture chapter. Totals may not sum due to independent rounding.

[1] 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.

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

Table 7-4: Emissions from Land Use, Land-Use Change, and Forestry (Gg)

Source Category	1990	2005	2006	2007	2008	2009	2010
CO_2	**8,117**	**8,933**	**8,754**	**9,233**	**9,618**	**8,247**	**8,369**
Cropland Remaining Cropland: Liming of Agricultural Soils	4,667	4,349	4,220	4,464	5,025	3,679	3,906
Urea Fertilization	2,417	3,504	3,656	3,757	3,601	3,480	3,480
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1,033	1,079	879	1,012	992	1,089	983
CH_4	**120**	**388**	**854**	**693**	**419**	**276**	**231**
Forest Land Remaining Forest Land: Forest Fires	120	388	854	693	419	276	231
N_2O	**10**	**27**	**53**	**45**	**29**	**21**	**19**
Forest Land Remaining Forest Land: Forest Fires	7	21	47	38	23	15	13
Forest Land Remaining Forest Land: Forest Soils[1]	+	1	1	1	1	1	1
Settlements Remaining Settlements: Settlement Soils[2]	3	5	5	5	5	5	5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+

+ Emissions are less than 0.5 Tg CO_2 Eq.

Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in the Agriculture chapter. Totals may not sum due to independent rounding.

[1] 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.

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

[BEGIN BOX]

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 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).[187] Additionally, the calculated emissions and sinks in a given year for the U.S. are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[188] 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 report presents

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

[188] See http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5270.php.

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.

[END BOX]

7.1. 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 fluxes over the inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country, (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series associated with the greenhouse gas inventory, such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories, and (3) account for greenhouse gas fluxes on all managed lands. The implementation of such a system helps to ensure that estimates of greenhouse gas fluxes are as accurate as possible. This section of the Inventory has been developed in order to comply with this guidance.

Multiple databases are used to track land management in the United States, which are also used as the basis to classify U.S. land area into the six IPCC land-use categories (i.e., *Forest Land Remaining Forest Land*, *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, *Wetlands Remaining Wetlands*, *Settlements Remaining Settlements* and *Other Land Remaining Other Land*) and thirty land-use change categories (e.g., *Cropland Converted to Forest Land*, *Grassland Converted to Forest Land*, *Wetlands Converted to Forest Land*, *Settlements Converted to Forest Land*, *Other Land Converted to Forest Lands*)[189] (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)[190] and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[191] Database. The U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD)[192] 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 786 million hectares, and this entire land base is considered managed.[193] In 2010, the United States had a total of 278 million hectares of Forest Land (a 4 percent increase since 1990), 159 million hectares of Cropland (down 6.6 percent since 1990), 258 million hectares of Grassland (down 3.9 percent since 1990), 26 million hectares of Wetlands (down 4.9 percent since 1990), 50 million hectares of Settlements (up 31 percent since 1990), and 14 million hectares of Other Land. It is important to note that the land base formally classified for the Inventory (see Table 7-5) is considered managed. Alaska is not formally included in the current land representation, but there is a planned improvement underway to include this portion of the United States in future inventories. In addition, wetlands are not differentiated between managed and unmanaged, although some wetlands would be unmanaged according to the U.S. definition (see definition later in this section). Future improvements will include a differentiation between managed and unmanaged wetlands. In addition, carbon stock changes are not currently estimated for the entire land base, which leads to discrepancies between the area data presented here and in the subsequent sections of the NIR. Planned improvements are underway or in development phases to conduct an inventory of carbon stock changes on all managed land (e.g., federal grasslands).

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 fifty states (Figure 7-1). 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. 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.

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[189] Land-use category definitions are provided in the Methodology section.

[190] NRI data is available at <http://www.ncgc.nrcs.usda.gov/products/nri/index.html>.

[191] FIA data is available at <http://fia.fs.fed .us/tools-data/data/>.

[192] NLCD data is available at <http://www.mrlc.gov/>.

[193] The current land representation does not include areas from Alaska or U.S. territories, but there are planned improvements to include these regions in future reports.

Table 7-5: Size of Land Use and Land-Use Change Categories on Managed Land Area by Land Use and Land Use Change Categories (thousands of hectares)

Land Use & Land-Use Change Categories[a]	1990	2005	2006	2007	2008	2009	2010
Total Forest Land	**267,120**	**274,649**	**275,355**	**276,060**	**276,780**	**277,486**	**278,213**
FF	262,008	262,354	263,505	264,585	265,298	265,997	266,717
CF	1,118	2,651	2,513	2,444	2,444	2,444	2,445
GF	3,425	7,821	7,564	7,297	7,299	7,301	7,303
WF	66	256	260	262	263	264	265
SF	103	371	378	386	387	388	389
OF	399	1,196	1,135	1,086	1,089	1,092	1,094
Total Cropland	**170,283**	**159,917**	**159,486**	**159,070**	**159,065**	**159,062**	**159,059**
CC	154,815	143,040	143,229	143,849	143,844	143,841	143,839
FC	1,118	675	612	568	568	568	568
GC	13,583	15,067	14,537	13,580	13,580	13,580	13,580
WC	156	193	183	174	174	174	174
SC	431	688	693	669	669	669	669
OC	180	253	234	231	231	231	231
Total Grassland	**268,149**	**260,543**	**259,825**	**259,202**	**258,668**	**258,144**	**257,600**
GG	257,937	241,419	241,090	241,452	241,016	240,588	240,143
FG	1,611	2,989	2,901	2,724	2,721	2,719	2,716
CG	7,902	14,609	14,301	13,598	13,504	13,411	13,314
WG	238	408	403	329	328	328	328
SG	111	274	275	267	267	267	267
OG	349	844	855	832	831	831	831
Total Wetlands	**27,483**	**26,941**	**26,809**	**26,606**	**26,444**	**26,286**	**26,124**
WW	26,834	25,432	25,330	25,167	25,009	24,853	24,695
FW	141	395	391	383	381	379	377
CW	132	365	356	345	345	345	345
GW	343	696	680	661	661	661	661
SW	0	10	10	10	10	10	10
OW	33	43	43	39	38	38	38
Total Settlements	**38,534**	**49,519**	**50,028**	**50,478**	**50,475**	**50,472**	**50,469**
SS	33,993	35,124	35,630	36,203	36,200	36,197	36,194
FS	1,787	6,111	6,133	6,089	6,089	6,089	6,089
CS	1,343	3,625	3,576	3,518	3,518	3,518	3,518
GS	1,353	4,430	4,459	4,436	4,436	4,436	4,436
WS	3	31	30	30	30	30	30
OS	55	198	200	201	201	201	201
Total Other Land	**14,276**	**14,275**	**14,341**	**14,428**	**14,412**	**14,395**	**14,379**
OO	13,242	12,054	12,070	12,137	12,121	12,105	12,089
FO	182	538	563	569	569	569	569
CO	331	645	665	703	703	703	703
GO	454	896	899	895	895	894	894
WO	65	121	123	104	103	103	103

SO	2		21	21	20	20	20	20
Grand Total	**785,845**		**785,845**	**785,845**	**785,845**	**785,845**	**785,845**	**785,845**

[a]The abbreviations are “F” for Forest Land, “C” for Cropland, “G” for Grassland, “W” for Wetlands, “S” for Settlements, and “O” for Other Lands. Lands remaining in the same land use category are identified with the land use abbreviation given twice (e.g., “FF” is Forest Land Remaining Forest Land), and land use change categories are identified with the previous land use abbreviation followed by the new land use abbreviation (e.g., “CF” is Cropland Converted to Forest Land).

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for wetlands which includes both managed and unmanaged lands based on the definitions for the current U.S. Land Representation Assessment. In addition, U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See Planned Improvements for discussion on plans to include Alaska and territories in future Inventories.

Figure 7-1. Percent of Total Land Area in the General Land-Use Categories for 2010

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 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, Grassland to Cropland, etc.), using surveys or other forms of data that do not provide location data on specific parcels of land. Approach 3 extends Approach 2 by providing location data on specific 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. All of these datasets have a spatially-explicit time series of land-use data, and therefore Approach 3 is used to provide a full representation of land use in the U.S. Inventory. 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 U.S. definitions of managed and unmanaged lands are 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 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. Managed land also includes legal protection of lands (e.g., wilderness, preserves, parks, etc.)

for conservation purposes (i.e., meets societal objectives).[194]

- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to human intervention due to the remoteness of the locations, or lands with essentially no development interest or protection due to limited personal, commercial or social value. Though these lands may be influenced indirectly by human actions such as atmospheric deposition of chemical species produced in industry, they are not influenced by a direct human intervention.[195]

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 U.S. 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,[196] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[197] 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 36.6 m wide and 0.4 ha in size with at least 10 percent cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land 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. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 36.6 m and continuous length of at least 110.6 m to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 36.6 m wide or 0.4 ha in size, otherwise they are excluded from Forest Land and classified as Settlements. Tree-covered areas in agricultural production settings, such as fruit orchards, or tree-covered areas in urban settings, such as city parks, are not considered forest land (Smith et al. 2009). NOTE: This definition applies to all U.S. lands and territories. However, at this time, data availability is limited for remote or inaccessible areas such as interior Alaska

- *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.[198] 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 alley cropping and windbreaks,[199] as well as lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[200]). 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

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[194] 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, however, 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. See the Planned Improvements section of the Inventory for work being done to refine the Wetland area estimates.

[195] There will be some areas that qualify as Forest Land or Grassland according to the land use criteria, but are classified as unmanaged land due to the remoteness of their location.

[196] See <http://socrates.lv-hrc.nevada.edu/fia/ab/issues/pending/glossary/Glossary_5_30_06.pdf>.

[197] See <http://www.nrcs.usda.gov/technical/land/nri01/glossary.html>.

[198] 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.

[199] 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.

[200] 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.

plants, forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands.[201] 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 addition to tundra are considered Grassland.[202] 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, 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 area estimates 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. 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 covered in other areas of the IPCC guidance and/or the inventory, including Cropland (e.g., rice cultivation), Grassland, and Forest Land (including drained or undrained 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 settlement category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland) are also included in Settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, non-settlement transportation corridors, and all land areas that do not fall into any of the other five land-use categories. It allows the total of identified land areas to match the managed national area.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main data sources for land area and use data in the United States are the NRI, FIA, and the NLCD. For the Inventory, the NRI is the official source of data on all land uses on non-federal lands (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 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 U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160-acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data 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. This Inventory incorporates data through 2007 from the NRI.

The FIA program, conducted by the USFS, is the official source of data on Forest Land area and management data for the Inventory. 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

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[201] 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.

[202] IPCC (2006) guidelines do not include provisions to separate desert and tundra as land categories.

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 had been conducted periodically, with all plots in a state being measured at a frequency of every 5 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 5 years. See Annex 3.12 to see the specific survey data available by state. The most recent year of available data varies state by state (2002 through 2009).

Though NRI provides land-area data for both federal and non-federal lands, it only includes land-use data on non-federal lands, and FIA only records data for forest land.[203] Consequently, major gaps exist when the datasets are combined, such as federal grassland operated by the Bureau of Land Management (BLM), USDA, and National Park Service, as well as most of Alaska.[204] 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, and 2006, has been applied over the conterminous United States (Homer et al. 2007), and also for Hawaii in 2001. For the conterminous United States, the NLCD Land Cover Change Products for 2001 and 2006 were used in order to represent both land use and land-use change for federal lands (Fry et al. 2011, Homer et al. 2007). 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 (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.

Another step in the analysis is to address gaps as well as overlaps in the representation of the U.S. land base between the Agricultural Carbon Stock Inventory (*Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*) and Forest Land Carbon Stock Inventory (*Forest Land Remaining Forest Land* and *Land Converted to Forest Land*), which are based on the NRI and FIA databases, respectively. NRI and FIA have different criteria for classifying forest land and sampling designs, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Moreover, 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. 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 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, respectively. In a second step, corresponding increases or decreases were made in the area estimates of Grassland and Wetland from the NRI and NLCD, 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).

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[203] 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.

[204] The 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 U.S. Territories.

As part of Quality Assurance /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, which is critical for conducting emission inventories and is provided from the NRI and FIA surveys. Consequently, the U.S. Census Survey was not adopted as the official land area estimate for the Inventory. Rather, the NRI data were adopted because this database provides full coverage of land area and land use for the conterminous United States and Hawaii. Regardless, the total difference between the U.S. Census Survey and the data sources used in the Inventory is about 25 million hectares for the total land base of about 786 million hectares currently included in the Inventory, or a 3.1 percent difference. Much of this difference is associated with open waters in coastal regions and the Great Lakes. NRI does not include as much of the area of open waters in these regions as the U.S. Census Survey.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the six IPCC land-use categories using definitions[205] developed to meet national circumstances, while adhering to IPCC (2006). In practice, the land was initially classified into a variety of land-use categories using the NRI, FIA and NLCD, and then aggregated into the thirty-six broad land use and land-use-change categories identified in IPCC (2006). Details on the approach used to combine data sources for each land use are described below as are the gaps that will be reconciled as part of ongoing planned improvements:

- *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, but NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports. Forest Lands in U.S. territories are currently excluded from the analysis, but FIA surveys are currently being conducted on U.S. territories and will become available in the future. NRI is being used in the current report to provide Forest Land areas on non-federal lands in Hawaii. Currently, federal forest land in Hawaii is evaluated with the 2001 NLCD, 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 C stocks and fluxes on Cropland. Croplands in U.S. territories are excluded from both NRI data collection and the NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.

- *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 C stocks and fluxes on Grassland. U.S. territories are excluded from both NRI data collection and the current release of the NLCD product. Grassland on federal Bureau of Land Management lands, Department of Defense lands, National Parks and within USFS lands are covered by the NLCD. In addition, federal and non-federal grasslands in Alaska are currently excluded from the analysis, but NLCD has a new product for Alaska that will be incorporated into the assessment for future reports.

- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while federal wetlands are covered by the NLCD. Alaska and U.S. territories are excluded. This currently includes both managed and unmanaged wetlands as no database has yet been applied to make this distinction. See Planned Improvements for details.

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[205] Definitions are provided in the previous section.

- *Settlements*: The 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 are covered by NLCD. Settlements in U.S. territories are currently excluded from NRI and NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.
- *Other Land*: Any land not falling into the other five land 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. Other land in U.S. territories is excluded from the NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.

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 initiated by distinguishing between managed and unmanaged lands. The managed lands are then assigned, from highest to lowest priority, in the following manner:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage or fiber. The consequence of this ranking is that crops in rotation with grass 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 and Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a single 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. In either case, emissions from Wetlands are included in the Inventory if human interventions are influencing emissions from Wetlands, in accordance with the guidance provided in IPCC (2006).

Recalculations Discussion

No major revisions were made to the time series for the current Inventory. However, new data were incorporated from FIA on forestland areas, which was used to make minor adjustments to the time series. FIA conducts a survey of plots annually so that each plot is visited every 5 years (Note: some states have not initiated the annual sampling regime, as discussed previously). Consequently, the time series is updated each year as new data are collected over the 5 year cycles.

Planned Improvements

Area data by land-use category are not estimated for major portions of Alaska or any of the U.S. territories. A key planned improvement is to incorporate land-use data from these areas into the Inventory. For Alaska, a new NLCD 2001 data product will be used to cover those land areas presently omitted. 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. Data sources will also be evaluated for representing land use on federal and non-federal lands in U.S.

territories.

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, and an analysis is planned 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 and Wetlands. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990 and 2000

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.

7.2. Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 5A1)

For estimating C stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2003):

- 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 necessary for estimating C flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

C 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, growth, mortality, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, clearing, 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 or 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 C of all vegetation 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. 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.

This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The net change in stocks for each pool is estimated, and then the changes in stocks are summed over 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. The change between inventories thus accounts for the C changes due to fires; however, it may not be possible to attribute the changes to the disturbance specifically. Similarly, 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 (2003) recommends reporting C stocks according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Currently, consistent datasets are just becoming available for the conterminous United States to allow forest land conversions and forest land remaining forest land to be identified, and research is ongoing to properly use that information based on research results. Thus, net changes in all forest-related land, including non-forest land converted to forest and forests converted to non-forest, are reported here.

Forest C storage pools, and the flows between them via emissions, sequestration, and transfers, are shown in Figure 7-2. 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 storage pools identified in this chapter. The storage pools identified in this chapter 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 7-2: Forest Sector Carbon Pools and Flows

Approximately 33 percent (304 million hectares) of the U.S. land area is forested (Smith et al. 2009). The current forest carbon inventory includes 275 million hectares in the conterminous 48 states (USDA Forest Service 2011a, 2011b) 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 Smith et al. (2009) and the forest land included in this report, which is based on USDA Forest Service (2011b). Survey data are not yet available from Hawaii and a large portion of interior Alaska, but estimates of these areas are included in Smith et al. (2009). Alternately, 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 carbon stock reported below. While Hawaii and U.S. territories have relatively small areas of forest land and will thus probably 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 Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture (USDA) Forest Service or the National Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

Sixty-eight percent of U.S. forests (208 million hectares) are classified as timberland, meaning they meet minimum levels of productivity. Nine percent of Alaskan forests overall and 81 percent of forests in the conterminous United States are classified as timberlands. Of the remaining nontimberland forests, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 66 million hectares are lower productivity forest lands (Smith et al. 2009). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest lands.

Forest land area declined by approximately 10 million hectares over the period from the early 1960s to the late 1980s. Since then, forest area has increased by about 12 million hectares (Smith et al. 2009). Current trends in forest area represent average annual change of 0.2 percent. 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 increases the eventual biomass density of the forest, thereby increasing the uptake of C.[206] Though harvesting forests removes much of the aboveground C, on average the volume of annual net growth nationwide is about 72 percent higher than the volume of annual removals on timberlands (Smith et al. 2009). The reversion of cropland to forest land increases C storage in biomass, forest floor, and soils. 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.

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 2009. The rate of forest clearing begun 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 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 and Nicholson 1998, Skog 2008). The size of these long-term C storage pools has increased during the last century.

Changes in C stocks in U.S. forests and harvested wood were estimated to account for net sequestration of 922 Tg CO_2 Eq. (251 Tg C) in 2010 (Table 7-6, Table 7-7, and Table 7-8). 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, average C in forest ecosystem biomass (aboveground and belowground) increased from 55 to 62 Mg C/ha between 1990 and 2011 (see Annex 3-12 for 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 2010 are the result of the sequences of new inventories for each state. C 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.

Annual net additions to HWP carbon stock were estimated to increase between 2009 and 2010 as inputs to products in use for both solid wood and paper products increased with limited recovery from the recession. Gross inputs to products in use in 2010 were just above the discard rate. The primary reason for overall net additions in recent years is a near stable rate of net additions to products in landfills.

Table 7-6: Net Annual Changes in C Stocks (Tg CO_2/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	2005	2006	2007	2008	2009	2010
Forest	**(569.6)**	**(835.5)**	**(854.9)**	**(856.2)**	**(856.2)**	**(856.2)**	**(856.2)**
Aboveground Biomass	(345.9)	(445.1)	(451.7)	(452.2)	(452.2)	(452.2)	(452.2)
Belowground Biomass	(67.8)	(87.8)	(89.0)	(89.1)	(89.1)	(89.1)	(89.1)
Dead Wood	(58.2)	(71.4)	(73.3)	(73.5)	(73.5)	(73.5)	(73.5)
Litter	(21.8)	(46.4)	(51.6)	(52.0)	(52.0)	(52.0)	(52.0)
Soil Organic Carbon	(75.8)	(184.8)	(189.4)	(189.4)	(189.4)	(189.4)	(189.4)
Harvested Wood	**(131.8)**	**(105.4)**	**(108.6)**	**(103.0)**	**(82.1)**	**(54.4)**	**(65.6)**
Products in Use	(64.8)	(45.4)	(45.1)	(39.1)	(19.1)	6.7	(4.4)
SWDS	(67.0)	(59.9)	(63.4)	(63.8)	(63.0)	(61.1)	(61.1)
Total Net Flux	**(701.4)**	**(940.9)**	**(963.5)**	**(959.2)**	**(938.3)**	**(910.6)**	**(921.8)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a portion of managed forests in Alaska, or trees

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[206] 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.

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 3.12. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 7-7: Net Annual Changes in C Stocks (Tg C/yr) in Forest and Harvested Wood Pools

Carbon Pool	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Forest	**(155.3)**	**(227.9)**	**(233.2)**	**(233.5)**	**(233.5)**	**(233.5)**	**(233.5)**
Aboveground Biomass	(94.3)	(121.4)	(123.2)	(123.3)	(123.3)	(123.3)	(123.3)
Belowground Biomass	(18.5)	(23.9)	(24.3)	(24.3)	(24.3)	(24.3)	(24.3)
Dead Wood	(15.9)	(19.5)	(20.0)	(20.1)	(20.1)	(20.1)	(20.1)
Litter	(6.0)	(12.7)	(14.1)	(14.2)	(14.2)	(14.2)	(14.2)
Soil Organic C	(20.7)	(50.4)	(51.6)	(51.6)	(51.6)	(51.6)	(51.6)
Harvested Wood	**(35.9)**	**(28.7)**	**(29.6)**	**(28.1)**	**(22.4)**	**(14.8)**	**(17.9)**
Products in Use	(17.7)	(12.4)	(12.3)	(10.7)	(5.2)	1.8	(1.2)
SWDS	(18.3)	(16.3)	(17.3)	(17.4)	(17.2)	(16.7)	(16.7)
Total Net Flux	**(191.3)**	**(256.6)**	**(262.8)**	**(261.6)**	**(255.9)**	**(248.3)**	**(251.4)**

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 Table 7-8. Together, the aboveground live and forest soil pools account for a large proportion of total forest C stocks. C stocks summed for non-soil pools increased over time Figure 7-3. Therefore, C sequestration was greater than C emissions from forests, as discussed above. Figure 7-4 shows county-average C densities for live trees on forest land, including both above- and belowground biomass.

Table 7-8: Forest area (1000 ha) and C Stocks (Tg C) in Forest and Harvested Wood Pools

	1990	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Forest Area (1000 ha)	**271,866**	**279,954**	**280,697**	**281,451**	**282,205**	**282,959**	**283,713**	**284,467**
Carbon Pools (Tg C)								
Forest	**39,108**	**41,395**	**41,623**	**41,857**	**42,090**	**42,324**	**42,557**	**42,791**
Aboveground Biomass	12,426	13,927	14,048	14,171	14,295	14,418	14,541	14,665
Belowground Biomass	2,458	2,755	2,778	2,803	2,827	2,851	2,876	2,900
Dead Wood	2,307	2,527	2,547	2,567	2,587	2,607	2,627	2,647
Litter	4,817	4,872	4,885	4,899	4,913	4,927	4,941	4,955
Soil Organic C	17,100	17,315	17,365	17,417	17,469	17,520	17,572	17,624
Harvested Wood	**1,859**	**2,354**	**2,383**	**2,412**	**2,434**	**2,449**	**2,466**	**2,487**
Products in Use	1,231	1,448	1,460	1,471	1,476	1,474	1,475	1,479
SWDS	628	906	923	941	958	974	991	1,008
Total C Stock	**40,967**	**43,749**	**44,007**	**44,268**	**44,524**	**44,772**	**45,023**	**45,278**

Note: Forest area estimates include portions of managed forests in Alaska for which survey data are available. 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 3.12. 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 2006 requires estimates of C stocks for 2006 and 2007.

Figure 7-3: Estimates of Net Annual Changes in C Stocks for Major C Pools

Figure 7-4: Average C Density in the Forest Tree Pool in the Conterminous United States, 2010

[BEGIN BOX]

Box 7-7-2: 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 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. forestland 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 being 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. CO_2 emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2010 were estimated to be 77.0 Tg CO_2/yr. This amount is masked in the estimate of net annual forest carbon stock change for 2010, however, because this net estimate accounts for the amount sequestered minus any emissions.

Table 7-9: Estimates of CO_2 (Tg/yr) emissions for the lower 48 states and Alaska[1]

Year	CO_2 emitted from Wildfires in Lower 48 States (Tg/yr)	CO_2 emitted from Prescribed Fires in Lower 48 States (Tg/yr)	CO_2 emitted from Wildfires in Alaska (Tg/yr)	Total CO_2 emitted (Tg/yr)
1990	33.1	7.3	+	40.1
2005	108.8	21.4	+	130.3
2006	261.7	25.3	+	287.0
2007	207.3	25.7	+	233.0
2008	123.9	15.7	+	139.6
2009	71.5	20.7	+	92.2
2010	56.7	20.3	+	77.0

+ Does not exceed 0.05 Tg CO_2 Eq.

[1] Note that 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.

[END BOX]

Methodology and Data Sources

The methodology described herein is consistent with IPCC (2003, 2006) and IPCC/UNEP/OECD/IEA (1997). Forest ecosystem C stocks and net annual C stock change are determined according to stock-difference methods, which involve applying C estimation factors to forest inventory data and interpolating between successive inventory-based estimates of C stocks. Harvested wood C estimates are 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 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 3.12 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 are made for the five IPCC C storage pools described above. All estimates are based on data collected from the extensive array of permanent forest inventory plots in the United States as well as models employed to fill gaps in field data (USDA Forest Service 2011b, 2011c). Carbon conversion factors are 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) is used. The Tier 3 biomass C values are from forest inventory tree-level data. The Tier 2 dead organic and soil C pools are based on empirical or process models from the inventory data. All carbon conversion factors are specific to regions or individual states within the U.S., which are 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 USDA Forest Service FIA program (Frayer and Furnival 1999, USDA Forest Service 2011b). Inventories include data collected on permanent inventory plots on forest lands[207] and are organized as a number of 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 2011d). Forest C calculations are organized according to these state surveys, and the frequency of surveys varies by state. All available data sets 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 (2010b) as the Forest Inventory and Analysis Database (FIADB) Version 4.0 (Woudenberg et al 2010). The set of FIADB 4.0 inventory data in use here were downloaded on 17 August 2011. However, to achieve consistent representation (spatial and temporal), three other general sources of past FIA data are 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 mostly to provide the data at or before 1990. Finally, an additional forest inventory data source is the Integrated Database (IDB), which is a compilation of periodic forest inventory data from the 1990s for California, Oregon, and Washington (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 (2011a) 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 in Annex 3.12.

Forest C stocks are 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), which have been formalized in an FIADB-to-carbon calculator (Smith et al. 2010). The conversion factors and model coefficients are categorized by region and forest type, and forest C stock estimates are calculated from application of these factors at the scale of FIA inventory plots. The results are estimates of C density (Mg C per hectare) for six forest ecosystem pools: live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil organic matter. The six carbon pools used in the FIADB-to-carbon calculator are aggregated to the 5 carbon pools defined by IPCC (2006): aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter. The live-tree and understory C are pooled as biomass, and standing dead trees and down dead wood are pooled as dead wood, in accordance with IPCC (2006).

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[207] Forest land in the United States includes land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood.

Once plot-level C stocks are calculated as C densities on *Forest Land Remaining Forest Land* for the five IPCC (2006) reporting pools, the stocks are 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 are summed to state or sub-state total C stocks. Annualized estimates of C stocks are developed by using available FIA inventory data and interpolating or extrapolating to assign a C stock to each year in the 1990 through 2011 time series. Flux, or net annual stock change, is estimated by calculating the difference in stocks between two successive years and applying the appropriate sign convention; net increases in ecosystem C are identified as negative flux. By convention, inventories are assigned to represent stocks as of January 1 of the inventory year; an estimate of flux for 1996 requires 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 3.12.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (d.b.h.) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for above- and below-ground biomass components. If inventory plots include data on individual trees, tree C is 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 do 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 are based on average densities (tonnes C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to 5 percent of the forest land inventory-plot-to-carbon conversions within the 177 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 d.b.h. In the current inventory, it is assumed that 10 percent of total understory C mass is belowground. Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory frequently represents over 1 percent of C in biomass, but its contribution rarely exceeds 2 percent of the total.

Carbon in Dead Organic Matter

Dead organic matter is initially calculated as three separate pools—standing dead trees, down dead wood, and litter—with C stocks estimated from sample data or modeled. The standing dead tree C pools include aboveground and belowground (coarse root) mass and include trees of at least 12.7 cm d.b.h. Calculations follow 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). Similarly to the situation with live tree data, some of the older forest inventory data do not provide sufficient data on standing dead trees to make accurate population-level estimates. The C estimates for these plots are based on average densities (tonnes C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to 26 percent of the forest land inventory-plot-to-carbon conversions within the 177 state-level surveys utilized here. Modeled estimates of down dead wood and litter are specific to regions and forest types within each region. Down 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. Down dead wood includes stumps and roots of harvested trees. Ratios of down dead wood to live tree biomass (Jenkins et al. 2003) are used to estimate this quantity. 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 equations of Smith and Heath (2002).

Carbon in Forest Soil

Soil organic C (SOC) 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 are based on the national STATSGO spatial database (USDA 1991), which includes region and soil type information. SOC determination is 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-present, but it does not reflect effects of past land use.

Harvested Wood Carbon

Estimates of the HWP contribution to forest C sinks and emissions (hereafter called "HWP Contribution") are 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 Parties to report 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 3.12 for more details about each approach). The United States uses the production accounting approach to report HWP Contribution. Under the production approach, C in exported wood is estimated as if it remains in the United States, and C in imported wood is 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 3.12). Annual estimates of change are 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).

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 are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are 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). Estimates for disposal of products reflect the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that are in sanitary landfills versus dumps.

There are five annual HWP variables that are 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 yields the estimate for HWP Contribution under the production accounting approach. A key assumption for estimating these variables is 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 3.12 for additional information. The 2010 flux estimate for forest C stocks is estimated to be between -1,035 and -808 Tg CO_2 Eq. at a 95 percent confidence level. This includes a range of -969 to -745 Tg CO_2 Eq. in forest ecosystems and -83 to -50 Tg CO_2 Eq. for HWP.

Table 7-10: Tier 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Forest Land Remaining Forest Land:

Changes in Forest C Stocks (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate [a]			
			(Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem	CO_2	(856.2)	(969.0)	(745.0)	(13.2)	13.0
Harvested Wood Products	CO_2	(65.6)	(83.2)	(49.9)	(26.9)	24.0
Total Forest	**CO_2**	**(921.8)**	**(1034.8)**	**(808.4)**	**(12.3)**	**12.3**

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 2010. 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 2011d).

Many key calculations for estimating current forest C stocks based on FIA data were developed to fill data gaps in assessing forest carbon 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 3.12). 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 4.0, which are available at an FIA internet site (USDA Forest Service 2011b). 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 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 with CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

In addition to annual updates to most-recent inventories for many states, five additional and notable changes in this year's inventory affected the national stock and change estimates for forest ecosystems. The basic models used to estimate HWP C stocks and change are unchanged from the previous Inventory. Adopting the method of Woodall et al. (2011a) for both live and standing dead trees affected these two pools in somewhat different ways. First, live tree C stocks are lower because the new method estimates lower biomass for most trees. However, the relative effect on net annual stock change was minimal and varied from state to state. Second, the change from modeled estimates of standing dead to the tree-based estimates (Woodall et al. 2011a, Domke et al. 2011, Woodall et al. In Press) also resulted in lower estimates of stocks, yet the newer stock-change estimates included greater sequestration throughout the 21-year interval. The remaining three changes to the Inventory originate as modifications in the forest inventory data, specifically the FIADB. A number of Sothern states revised some previously-existing inventories from the late 1990s and early 2000s. From this, stock and stock-change estimates varied slightly for seven states over the mid-part of the 1990 through2010 interval. In some cases, C stocks increased while in others they decreased. The net effect is a slight increase in sequestration as estimated for the late 1990s and early 2000s. The fourth change is the addition of the periodic data for Alaska timberlands so that a stock-change estimate is now included for a large part of coastal Alaska. The net effect on the national totals is a slight increase in sequestration applied throughout the interval. Finally, forest area, and thus C stock, estimates were revised upward for central and western portions of Oklahoma and Texas since the previous Inventory report. These changes only affect stocks and not change because those forest lands are based on single current surveys only.

The changes in estimation procedures for live and standing dead trees affected estimates of uncertainty. The CRM method, which is largely a function of tree volume, appears to reduce levels of individual-tree error for both live and standing dead trees. In addition, empirical (i.e., field-based measurements of individual trees) estimates of standing dead trees have replaced a stand-level model, which should further reduce error. Additional information regarding error associated with the volume and CRM models remains limited and is an active area of ongoing research (e.g., FIA National Volume/Biomass Study).

Planned Improvements

The ongoing annual surveys by the FIA Program will improve precision of forest C estimates as new state surveys become available (USDA Forest Service 2011b), particularly in western states. The annual surveys will eventually include all states. To date, three states are not yet reporting any data from the annualized sampling design of FIA: Hawaii, New Mexico and Wyoming. Estimates for these states are currently based on older, periodic data. Hawaii and U.S. territories will also be included when appropriate forest C data are available. In addition, the more intensive sampling of down dead wood, litter, and soil organic C on some of the permanent FIA plots continues and will substantially improve resolution of C pools at the plot level for all U.S. forest land as this information becomes available (Woodall et al. 2011b). Improved resolution, incorporating more of Alaska's forests, and using annualized sampling data as it becomes available for those states currently not reporting are planned for future reporting.

As more information becomes available about historical land use, the ongoing effects of changes in land use and forest management will be better accounted for in estimates of soil C (Birdsey and Lewis 2003, Woodbury et al. 2006, Woodbury et al. 2007). Currently, soil C estimates are based on the assumption that soil C density depends only on broad forest type group, not on land-use history, but long-term residual effects on soil and forest floor C stocks are likely after land-use change. Estimates of such effects depend on identifying past land use changes associated with forest lands.

Similarly, agroforestry practices, such as windbreaks or riparian forest buffers along waterways, are not currently accounted for in the inventory. In order to properly account for the C stocks and fluxes associated with agroforestry, research will be needed that provides the basis and tools for including these plantings in a nation-wide inventory, as well as the means for entity-level reporting.

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 2010 were estimated to be 4.8 Tg CO_2 Eq. of CH_4 and 4.0 Tg CO_2 Eq. of N_2O, as shown in Table 7-11 and Table 7-12**.** 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 7-11: Estimated Non-CO_2 Emissions from Forest Fires (Tg CO_2 Eq.) for U.S. Forests[1]

Gas	1990	2005	2006	2007	2008	2009	2010
CH_4	2.5	8.2	18.1	14.7	8.8	5.8	4.8
N_2O	2.1	6.7	14.7	12.0	7.2	4.7	4.0
Total	**4.6**	**14.9**	**32.8**	**26.6**	**16.0**	**10.5**	**8.8**

[1] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

Table 7-12: Estimated Non-CO_2 Emissions from Forest Fires (Gg Gas) for U.S. Forests[1]

Gas	1990	2005	2006	2007	2008	2009	2010
CH_4	121	390	860	698	418	276	231
N_2O	7	22	48	39	23	15	13

[1] Calculated based on C emission estimates *in Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

Methodology

The IPCC (2003) Tier 2 default methodology was used to calculate non-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.** 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 7-13-8) 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 were:**

$$CH_4 \text{ Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (CH_4 \text{ to } CO_2 \text{ emission ratio})$$

$$N_2O \text{ Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (N_2O \text{ to } CO_2 \text{ emission ratio})$$

Estimates for C emitted from forest fires are the same estimates used to generate estimates of CO_2 presented earlier in Box 7-1. 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 3.12 for more details on the methodology used to estimate C emitted from forest fires.

Table 7-13: Estimated Carbon Released from Forest Fires for U.S. Forests

Year	C Emitted (Tg/yr)
1990	11.9
2005	38.3
2006	84.4
2007	68.5
2008	41.0
2009	27.1
2010	22.6

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 (Tier 2) uncertainty analysis was performed using information about the uncertainty surrounding each of these variables. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-14.

Table 7-14: Tier 2 Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires in Forest Land Remaining Forest Land (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	4.8	1.0	12.0	−79%	+148%
Non-CO_2 Emissions from Forest Fires	N_2O	4.0	0.8	9.8	−79%	+147%

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2010. 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. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

This is the Inventory report in which non-CO_2 emissions were calculated using the 2006 IPCC default emission factors for CH_4 and N_2O instead of the 2003 IPCC default emission factors. These default emission factors were converted to CH_4 to CO_2 and N_2O to CO_2 emission ratios and then multiplied by CO_2 emissions to estimate CH_4 and N_2O emissions. The previous 2003 IPCC methodology provides emission ratios that are multiplied by total C emitted.

The National Association of State Foresters (NASF) releases data on land under wildland protection every several years. In 2011, NASF released these data for the year 2008, which affected the ratio of forest land to land under wildland protection for the years 2007 through 2009. For each of these three years, the updated ratio decreased the forest area burned estimates for the lower forty-eight states by around 15 percent. See the explanation in Annex 3.12 for more details on how the forestland to land under wildland protection ratio is used to calculate forest fire emissions.

In previous Inventory reports, the methodology has assumed that the C density of forest areas burned in wild and prescribed fires does not vary between years. This assumption has been in contrast to the forest C stock estimates, which are updated annually for all years based on data from the USDA Forest Service. The methodology adopted for the current Inventory improves the C density factors by incorporating dynamic C density values based on the annual C pool data provided by the USDA Forest Service for the years 1990 to 2010. As a result of this update, estimates of CO_2 and non-CO_2 emissions from wild and prescribed fires decreased by between 20 and 30 percent as compared to the estimates included in the previous Inventory. This decrease occurred because the dynamic C density values calculated were 20 to30 percent lower (depending on the year) than the C density values previously used for the methodology. For more information on how C density contributes to estimates of emissions from forest fires, see Annex 3.12.

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.

Direct N_2O Fluxes from Forest Soils (IPCC Source Category 5A1)

Of the synthetic 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 cropped 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 approximately 20 years later). 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 average annual application is quite low as inferred by dividing all forest land that may undergo N fertilization at some point during its growing cycle by the amount of N fertilizer added to these forests in a given year. Direct N_2O emissions from forest soils in 2010 were 0.4 Tg CO_2 Eq. (1 Gg). Emissions have increased by 455 percent from 1990 to 2010 as a result of an increase in the 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 7-15.

Table 7-15: Direct N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Gg N_2O)

Year	Tg CO_2 Eq.	Gg
1990	0.1	0.2
2005	0.4	1.2
2006	0.4	1.2
2007	0.4	1.2
2008	0.4	1.2
2009	0.4	1.2
2010	0.4	1.2

Note: These estimates include direct N_2O emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Forest Land Remaining Forest Land* and from *Land Converted to Forest Land.*

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, 2006, 2007 and 2008, 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 (~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. 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. The volatilization and leaching/runoff N fractions for forest land, calculated according to the IPCC default factors of 10 percent and 30 percent, respectively, were included with the indirect emissions in the Agricultural Soil Management source category (consistent with reporting guidance that all indirect emissions are included in the Agricultural Soil Management source category).

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[208] of uncertainty at ±50 percent, and area receiving fertilizer was assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with direct N_2O emission factor for synthetic N fertilizer application to soils. Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2010 emissions estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-16. N_2O fluxes from soils were estimated to be between 0.1 and 1.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2010 emission estimate of 0.4 Tg CO_2 Eq.

Table 7-16: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate**			
			(Tg CO_2 Eq.)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Forest Land Remaining Forest Land: N_2O Fluxes from Soils	N_2O	0.4	0.1	1.1	-59%	+211%

Note: This estimate includes direct N_2O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Planned Improvements

State-level area data will be acquired for southeastern pine plantations and northwestern Douglas-fir forests receiving fertilizer to estimate soil N_2O emission by state and provide information about regional variation in emission patterns.

7.3. Land Converted to Forest Land (IPCC Source Category 5A2)

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. However, the magnitude of these changes is not currently known. Given the paucity of available land-use information relevant to this particular IPCC source category, 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.

7.4. Cropland Remaining Cropland (IPCC Source Category 5B1)

Mineral and Organic Soil Carbon Stock Changes

Soils contain both organic and inorganic forms of C, but soil organic C (SOC) stocks are the main source and sink

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[208] Uncertainty is unknown for the fertilization rates so a conservative value of ±50% was used in the analysis.

for atmospheric CO_2 in most soils. Changes in inorganic C stocks are typically minor. In addition, soil organic C is the dominant organic C pool in cropland ecosystems, because biomass and dead organic matter have considerably less C and those pools are relatively ephemeral. IPCC (2006) recommends reporting changes in soil organic C stocks due to agricultural land-use and management activities on mineral and organic soils.[209]

Typical well-drained mineral soils contain from 1 to 6 percent organic C by weight, although mineral soils that are saturated with water for substantial periods during the year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural uses can cause as much as half of the SOC to be decomposed and the C lost to the atmosphere. The rate and ultimate magnitude of C loss will depend on pre-conversion conditions, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40 to 60 percent of the C loss generally occurs within the first 10 years following conversion; C stocks continue to decline in subsequent decades but at a much slower rate. In temperate regions, C loss can continue for several decades, reducing stocks by 20 to 40 percent of native C levels. 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. However, land use, management, and other conditions may change before the new equilibrium is reached. The quantity and quality of organic matter inputs and their rate of decomposition are determined by the combined interaction of climate, soil properties, and land use. Land use and 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 pool of soil C.

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), forming under inundated conditions in which minimal decomposition of plant residue occurs. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil, which accelerates the rate of decomposition and CO_2 emissions. Because of the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time. The rate of CO_2 emissions varies depending on climate and composition (i.e., decomposability) of the organic matter. Also, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests, due to deeper drainage and more intensive management practices in cropland (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997). Carbon losses are estimated from drained organic soils under both grassland and cropland management in this Inventory.

Cropland Remaining Cropland includes all cropland in an inventory year that had been cropland for the last 20 years[210] according to the USDA NRI land-use survey (USDA-NRCS 2009). The Inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but there is a minor amount of cropland on federal lands that is not currently included in the estimation of C stock changes, leading to a discrepancy between the total amount of managed area in *Cropland Remaining Cropland* (see Section 7.1) and the cropland area included in the Inventory. It is important to note that plans are being made to include federal croplands in future C inventories.

The area of *Cropland Remaining Cropland* changes through time as land is converted to or from cropland management. CO_2 emissions and removals[211] due to changes in mineral soil C stocks are estimated using a Tier 3 approach for the majority of annual crops. A Tier 2 IPCC method is used for the remaining crops (vegetables, tobacco, perennial/horticultural crops, and rice) not included in the Tier 3 method. 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 stocks that were not addressed with the Tier 3 approach (i.e., change in C stocks after 2003 due to Conservation Reserve Program enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method.

Of the two sub-source categories, land-use and land management of mineral soils was the most important component of total net C stock change between 1990 and 20010 (see Table 7-17 and Table 7-18). In 2010, mineral soils were estimated to remove 43.1 Tg CO_2 Eq. (11.7 Tg C). This rate of C storage in mineral soils represented

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[209] CO_2 emissions associated with liming are also estimated but are included in a separate section of the report.

[210] 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.

[211] Note that removals occur through crop and forage uptake of CO_2 into biomass C that is later incorporated into soil pools.

about a 30 percent decrease in the rate since the initial reporting year of 1990. Emissions from organic soils were 26.8 Tg CO_2 Eq. (7.3 Tg C) in 2010. In total, U.S. agricultural soils in *Cropland Remaining Cropland* removed approximately 16.3 Tg CO_2 Eq. (4.4 Tg C) in 2009.

Table 7-17: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Soil Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Mineral Soils	(61.7)	(45.7)	(46.6)	(47.1)	(45.5)	(44.9)	(43.1)
Organic Soils	26.3	26.8	26.8	26.8	26.8	26.8	26.8
Total Net Flux	**(35.4)**	**(18.9)**	**(19.8)**	**(20.3)**	**(18.7)**	**(18.1)**	**(16.3)**

Note: Mineral soil estimates are based on the previous Inventory due to delays in the analysis. Estimates will be updated after public review.

Table 7-18: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg C)

Soil Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Mineral Soils	(16.8)	(12.5)	(12.7)	(12.9)	(12.4)	(12.2)	(11.7)
Organic Soils	7.2	7.3	7.3	7.3	7.3	7.3	7.3
Total Net Flux	**(9.7)**	**(5.2)**	**(5.4)**	**(5.5)**	**(5.1)**	**(4.9)**	**(4.4)**

Note: Mineral soil estimates are based on the previous Inventory due to delays in the analysis. Estimates will be updated after public review.

Figure 7-5: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2010, *Cropland Remaining Cropland* [Maps will be provided in public review version]

Figure 7-6: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2010, *Cropland Remaining Cropland* [Maps will be provided in public review version]

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks due to: (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils for *Cropland Remaining Cropland.*

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 National Resources Inventory (NRI) survey (USDA-NRCS 2009). The NRI is a statistically-based sample of all non-federal land, and includes approximately 529,687 points in agricultural land for the conterminous United States and Hawaii.[212] 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, and 1994-1997). However, the NRI program began collecting annual data in 1998, and data are currently available through 2007. NRI points were classified as *Cropland Remaining Cropland* in a

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[212] NRI points were classified as agricultural if under grassland or cropland management between 1990 and 2007.

given year between 1990 and 2007 if the land use had been cropland for 20 years.[213] Cropland includes all land used to produce food and 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 was applied to estimate C stock changes for mineral soils used to produce a majority of annual crops in the United States (Ogle et al. 2010, Ogle et al. in prep). 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 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 are taken into account 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 vegetables, tobacco, perennial/horticultural crops, rice, and crops 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 to address its adequacy for estimating C stock changes associated with certain crops and rotations, as well as cobbly, gravelly, or shaley soils. An additional stock change calculation was made for mineral soils using Tier 2 emission factors, accounting for enrollment patterns in the Conservation Reserve Program after 2007, which was not addressed by the Tier 3 methods.

Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.13.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates the dynamics of C and other elements in cropland, grassland, forest, and savanna ecosystems. The DAYCENT model utilizes the soil C modeling framework developed in 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 250m. 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 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 computes 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 nutrient (N, K, S) elements. This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC, because the simulation model treats changes as continuous over time rather than the simplified discrete changes represented in the default method (see Box 7-3 for additional information). National estimates were obtained by simulating historical land-use and management patterns as recorded in the USDA National Resources Inventory (NRI) survey.

[BEGIN BOX]

Box 7-3: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

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[213] 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.

A Tier 3 model-based approach is used to inventory soil C stock changes on the majority of agricultural land with mineral soils. This approach entails several fundamental differences compared to the IPCC Tier 1 or 2 methods, which are based on a classification of land areas into a number of discrete classes based on a highly aggregated classification of climate, soil, and management (i.e., only six climate regions, seven soil types and eleven management systems occur in U.S. agricultural land under the IPCC classification). Input variables to the Tier 3 model, including climate, soils, and management activities (e.g., fertilization, crop species, tillage, etc.), are represented in considerably more detail both temporally and spatially, and exhibit multi-dimensional interactions through the more complex model structure compared with the IPCC Tier 1 or 2 approach. The spatial resolution of the analysis is also finer in the Tier 3 method compared to the lower tier methods as implemented in the United States for previous Inventories (e.g., 3,037 counties versus 181 Major Land Resource Areas (MLRAs), respectively).

In the DAYCENT model (i.e., daily time-step version of the Century model), soil C dynamics (and CO_2 emissions and uptake) are treated as continuous variables, which change on a monthly time step. Carbon emissions and removals are an outcome of plant production and decomposition processes, which are simulated in the model structure. Thus, changes in soil C stocks are influenced by not only changes in land use and management but also inter-annual climate variability and secondary feedbacks between management activities, climate, and soils as they affect primary production and decomposition. This latter characteristic constitutes one of the greatest differences between the methods, and forms the basis for a more complete accounting of soil C stock changes in the Tier 3 approach compared with Tier 2 methodology.

Because the Tier 3 model simulates a continuous time period rather than the equilibrium step change used in the IPCC methodology (Tier 1 and 2), the Tier 3 model addresses the delayed response of soils to management and land-use changes. Delayed responses can occur due to variable weather patterns and other environmental constraints that interact with land use and management and affect the time frame over which stock changes occur. Moreover, the Tier 3 method also accounts for the overall effect of increasing yields and, hence, C input to soils that have taken place across management systems and crop types within the United States. Productivity has increased by 1 to 2 percent annually over the past 4 to 5 decades for most major crops in the United States (Reilly and Fuglie 1998), which is believed to have led to increases in cropland soil C stocks (e.g., Allmaras et al. 2000). This is a major difference from the IPCC-based Tier 1 and 2 approaches, in which trends in soil C stocks only capture discrete changes in management and/or land use, rather than a longer term trend such as gradual increases in crop productivity.

[END BOX]

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 3.13 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 6.2, and Annex 3.10.

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, which were obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). Each NRI point was run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. Carbon stock estimates from DAYCENT were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007, 2010). C stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but C stock changes from 2008 to 2010 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years.

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 to apply appropriate stock change factors. MLRAs formed the base spatial unit for mapping climate regions in the United States; each MLRA represents 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).

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 (2003, 2006). Changing the reference condition was necessary because soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than those that are not considered cultivated cropland.

U.S.-specific stock change factors were derived from published literature to determine the impact of management practices on SOC storage, including changes in tillage, cropping rotations and intensification, and land-use change between cultivated and uncultivated conditions (Ogle et al. 2003, Ogle et al. 2006). U.S. factors associated with organic matter amendments were not estimated because there were an insufficient number of studies to analyze those impacts. Instead, factors from IPCC (2003) were used to estimate the effect of those activities. Euliss and Gleason (2002) provided the data for computing the change in SOC storage resulting from restoration of wetland enrolled in the Conservation Reserve Program.

Activity data were primarily based on the historical land-use/management patterns recorded in the NRI. 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 previous methodology subsection on the Tier 3 analysis for mineral soils.

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 the 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 2010 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 1990 and 2010 were adjusted to account for additional C stock changes associated with gains or losses in soil C after 2007 due to changes in Conservation Reserve Program enrollment. The change in enrollment acreage relative to 2007 was based on data from USDA-FSA (2011) for 2008 through 2010, and 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 estimations using the IPCC method (see Annex 3.13 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 (2003, 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 1992, 1997, 2002 and 2007 *Cropland Remaining Cropland* areas from the 2007 *National Resources Inventory* (USDA-NRCS 2009). The annual emissions estimated for 1992 was applied to 1990 through 1992; annual emissions estimated for 1997 was applied to 1993 through 1997; annual emissions estimated for 2002 was applied to 1998 through 2002; and annual emissions estimated for 2007 was applied to 2003 through 2010.

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 7-19 for each subsource (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 3.13 for further discussion). A combined uncertainty estimate for changes in soil C stocks is also included. Uncertainty estimates from each component 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. More details on how the individual uncertainties were developed are in Annex 3.13. The combined uncertainty for soil C stocks in *Cropland Remaining Cropland* ranged from 183 percent below to 184 percent above the 2010 stock change estimate of -16.3 Tg CO_2 Eq.

Table 7-19: Tier 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (Tg CO_2 Eq. and Percent)

Source	2010 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate			
		(Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology*	(42.3)	(69.6)	(15.1)	(64)	64
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)	2.1	3.1	(50)	(50)	50
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	26.8	17.7	39.0	(34)	46
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(16.3)**	**(46.1)**	**13.7**	**(183)**	**184**

Note: Tier 3 mineral soil estimates are based on last year's inventory due to delays in the analysis. Estimates will be updated after public review.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. 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) use of the DAYCENT biogeochemical model to estimate soil organic C stock changes for the Tier 3 method; 2) incorporation of MODIS Enhanced Vegetation Index as to reduce uncertainties in the estimation of crop production and subsequent carbon input to the soil; 3) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 4) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; 5) extension of the tillage activity dataset with statistics from Conservation Technology and Information Center (CTIC 2004); and 6) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2011). *The influence of these changes on the time series is still being evaluated, but more information will be available after public review.*

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. 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 40 long-term experiments, representing about 800 combinations of management treatments across all of the sites (Ogle et al. 2007). Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors. *The quality control measures are ongoing and will be finalized with inventory estimates after public review for the Tier 3 mineral soil estimates.*

Planned Improvements

An automated quality assurance/quality control system is currently under development for the Tier 3 method that is used to estimate the majority of emissions associated with this source category. Currently, quality control is conducted by manual graphing and queries to determine if values are outside of an expected range. The new system will automatically create graphs, maps and conduct range checking to improve efficiency in this important step for the inventory analysis. This development will ensure a more thorough review of the inventory results.

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 ameliorate 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, climate regime, and the type of mineral applied. Emissions from liming have fluctuated over the past nineteen years, ranging from 3.8 Tg CO_2 Eq. to 5.0 Tg CO_2 Eq. In 2010, liming of agricultural soils in the United States resulted in emissions of 3.9 Tg CO_2 Eq. (1.1 Tg C), representing about a 16 percent decrease in emissions since 1990 (see Table 7-20 and Table 7-21). The trend is driven entirely by the amount of lime and dolomite estimated to have been applied to soils over the time period.

Table 7-20: Emissions from Liming of Agricultural Soils (Tg CO_2 Eq.)

Source	1990		2005	2006	2007	2008	2009	2010
Liming of Soils[1]	4.7		4.3	4.2	4.5	5.0	3.7	3.9

Note: Shaded areas indicate values based on a combination of data and projections. All other values are based on data only.

[1] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements*.

Table 7-21: Emissions from Liming of Agricultural Soils (Tg C)

Source	1990		2005	2006	2007	2008	2009	2010
Liming of Soils[1]	1.3		1.2	1.2	1.2	1.4	1.0	1.1

Note: Shaded areas indicate values based on a combination of data and projections. All other values are based on data only.

[1] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements*.

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 7-22) 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, b, 2009 through 2011; USGS 2008 through 2011). 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).

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 2010 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 2010 data, the previous year's fractions were applied to a 2009 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2011* (USGS 2011); thus, the 2010 data in Table 7-20 through Table 7-22 are shaded to indicate that they are based on a combination of data and projections.

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.

Table 7-22: Applied Minerals (Million Metric Tons)

Mineral	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Limestone	19.01		18.09	16.54	17.46	20.46	15.58	16.55
Dolomite	2.36		1.85	2.73	2.92	2.55	1.31	1.39

Note: Data represent amounts applied to *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*, and *Settlements Remaining Settlements*. Shaded areas indicate values based on a combination of data and projections. All other values are based on data only.

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 2003b). 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 (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 emissions from liming. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-23. Carbon dioxide emissions from Liming of Agricultural Soils in 2010 were estimated to be between 0.11 and 8.27 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 97 percent below to 112 percent above the 2010 emission estimate of 3.91 Tg CO_2 Eq.

Table 7-23: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming of Agricultural Soils[1]	CO_2	3.9	0.11	8.27	-97%	+112%

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

[1] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland,* and *Settlements Remaining Settlements*.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2010. 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

Several adjustments were made in the current Inventory to improve the results. The quantity of applied minerals reported in the previous inventory for 2008 has been revised; the updated activity data for 2008 for limestone are approximately 6,000 thousand metric tons greater and the 2008 data for dolomite are approximately 400 thousand metric tons less than the data used for the previous inventory, consequently, the reported emissions resulting from liming in 2008 decreased by about 0.3 percent. In the previous inventory, to estimate 2009 data, the previous year's fractions were applied to a 2009 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2010* (USGS 2010). 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 2009. These values have replaced those used in the previous inventory to calculate the quantity of minerals applied to soil and the emissions from liming. The updated activity data for 2009 are approximately 40,496 thousand metric tons less than the data used in the previous Inventory. As a result, the reported emissions from liming in 2009 decreased by about 13 percent.

CO_2 Emissions from Urea Fertilization

The use of urea ($CO(NH_2)_2$) as fertilizer leads to emissions of CO_2 that was fixed during the industrial production process. Urea in the presence of water and urease enzymes 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 3.5 Tg CO_2 Eq. (0.9 Tg C) in 2010 (Table 7-24 and Table 7-25). Emissions from urea fertilization have grown 44 percent between 1990 and 2010, due to an increase in the use of urea as fertilizer.

Table 7-24: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Source	1990		2005	2006	2007	2008	2009	2010
Urea Fertilization[1]	2.4		3.5	3.7	3.8	3.6	3.5	3.5

Note: Shaded areas indicate values based on a combination of data and projections. All other values are based on data only.

[1] 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.*

Note: 2009 and 2010 values will be updated in the final draft of this Inventory, upon incorporation of newly available data from AAPFCO (2011b).

Table 7-25: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg C)

Source	1990		2005	2006	2007	2008	2009	2010
Urea Fertilization[1]	0.7		1.0	1.0	1.0	1.0	0.9	0.9

Note: Shaded areas indicate values based on a combination of data and projections. All other values are based on data only.

[1] 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.*

Note: 2009 and 2010 values will be updated in the final draft of this Inventory, upon incorporation of newly available data from AAPFCO (2011b).

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The annual amounts of urea fertilizer applied (see Table 7-26) were derived from state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2011b) and were multiplied by the default IPCC (2006) emission factor of 0.20, which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July through June), a calculation was performed to convert the data to calendar years (January through December). According to historic monthly fertilizer use data (TVA 1992b), 65 percent of total fertilizer used in any fertilizer year is applied between January and June of that calendar year, and 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year. Since 2011 fertilizer year data were not available, July through December 2010 fertilizer consumption was estimated by calculating the percent change in urea use from January through June 2009 to January through June 2010. This percent change was then multiplied by the July through December 2009 data to estimate July through December 2010 fertilizer use; thus, the 2010 data in Table 7-24 through Table 7-26 are shaded to indicate that they are based on a combination of data and projections (note that in the tables, 2009 is also shaded because the numbers shown in the tables do not yet include the 2010 data, which are now available; once these data are incorporated in the final draft of this Inventory, the numbers will accurately reflect the methodology outlined in this paragraph). 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.

Table 7-26: Applied Urea (Million Metric Tons)

	1990		2005	2006	2007	2008	2009	2010
Urea Fertilizer[1]	3.30		4.78	4.98	5.12	4.91	4.75	4.75

Note: Shaded areas indicate values based on a combination of data and projections. All other values are based on data only.

[1] Data 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.*

Note: Values will be updated in the final draft of this Inventory, upon incorporation of newly available data from AAPFCO (2011b).

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 7-27 for Urea Fertilization. A Tier 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C 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 high. 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 MT 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. Carbon dioxide emissions from urea fertilization of agricultural soils in 2010 were estimated to be between 2.01 and 3.59 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 42 percent below to 3 percent above the 2010 emission estimate of 3.48 Tg CO_2 Eq.

Table 7-27: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	3.48	2.01	3.59	-42%	+3%

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

Note: 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*.

Note: Uncertainty estimates will be updated in the final draft of this Inventory, upon incorporation of newly available data from AAPFCO (2011b).

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2010. 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. Inventory reporting forms and text were reviewed. No errors were found.

Recalculations Discussion

The current Inventory has been updated relative to the previous report. July to December 2008 urea application data were updated with assumptions for fertilizer year 2009, and the 2008 emission estimate was revised accordingly. The activity data increased about 1,620 metric tons for 2008 and this change resulted in an approximately 0.03 percent increase in emissions in 2008 relative to the previous Inventory. In the previous Inventory, the application for this period was calculated based on application during July to December 2007. January to June 2009 and July to December 2009 data were also used to update 2009 emission estimates. The activity data decreased about 60,880 metric tons for 2009, resulting in an approximately 1.2 percent decrease in emissions in 2009 relative to 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.

7.5. Land Converted to Cropland (IPCC Source Category 5B2)

Land Converted to Cropland includes all cropland in an inventory year that had been another land use at any point during the previous 20 years[214] according to the USDA NRI land-use survey (USDA-NRCS 2009). Consequently, lands are retained in this category for 20 years as recommended by the IPCC guidelines (IPCC 2006) unless there is another land-use change. The Inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but there is a minor amount of cropland on federal lands that is not currently included in the estimation of C stock changes, leading to a discrepancy between the total amount of managed area in *Land Converted to Cropland* (see Section 7.1) and the cropland area included in the Inventory. It is important to note that plans are being made to include these areas in future C inventories.

Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Cropland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. The IPCC (2006) recommends reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[215]

Land-use and management of mineral soils in *Land Converted to Cropland* led to losses of C throughout the time series (Table 7-28 and Table 7-29). The total rate of change in soil C stocks was 20.0 Tg CO_2 Eq. (5.4 Tg C) in 2010. Mineral soils were estimated to lose 18.8 Tg CO_2 Eq. (5.1 Tg C) in 2010, while drainage and cultivation of organic soils led to an annual loss of 1.1 Tg CO_2 Eq. (0.3 Tg C) in 2010.

Table 7-28: Net CO_2 Flux from Soil C Stock Changes in Land *Converted to Cropland* (Tg CO_2 Eq.)

Soil Type	1990		2005	2006	2007	2008	2009	2010
Mineral Soils	32.2		18.9	19.1	18.8	18.8	18.8	18.8
Organic Soils	2.2		1.1	1.1	1.1	1.1	1.1	1.1
Total Net Flux	**34.3**		**20.1**	**20.3**	**20.0**	**20.0**	**20.0**	**20.0**

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review.

Table 7-29: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (Tg C)

Soil Type	1990		2005	2006	2007	2008	2009	2010
Mineral Soils	8.8		5.2	5.2	5.1	5.1	5.1	5.1
Organic Soils	0.6		0.3	0.3	0.3	0.3	0.3	0.3
Total Net Flux	**9.4**		**5.5**	**5.5**	**5.4**	**5.4**	**5.4**	**5.4**

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review.

Figure 7-7: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2010, *Land Converted to Cropland* [Maps will be provided in public review version]

Figure 7-8: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2010, *Land Converted to Cropland* [Maps will be provided in public review version]

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[214] 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.

[215] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils for *Land Converted to Cropland*. Biomass C stock changes are not explicitly included in this category but losses of associated with conversion of forest to grassland 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 3.13.

Soil C stock changes were estimated for *Land Converted to Cropland* according to land-use histories recorded in the 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. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2007. 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

A Tier 3 model-based approach was applied to estimate C stock changes for soils on *Land Converted to Cropland* used to produce a majority of all crops (Ogle et al. 2010; Ogle et al., in prep). 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 vegetable, tobacco, perennial/horticultural crops, and rice; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.[216]

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical model for the Tier 3 methods (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DAYCENT model utilizes the soil C modeling framework developed in 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 National Resources Inventory (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 2010 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years. 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 (see *Cropland Remaining Cropland* Tier 3 methods section and Annex 3.13 for additional information).

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 *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 2 methods section for additional information).

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 (2003, 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 1992, 1997, 2002 and 2007 *Land Converted to Cropland* areas from the 2007 *National Resources Inventory* (USDA-NRCS 2009). The annual emissions estimated for 1992 was applied to 1990 through 1992; annual emissions estimated for 1997 was applied to 1993 through 1997; annual emissions estimated for 2002 was applied to 1998 through 2002; and annual emissions estimated for 2007 was applied to 2003 through 2010.

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[216] 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).

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described for *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-30 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 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component 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 is currently not available, but will be provided after public review.

Table 7-30: Tier 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Cropland* (Tg CO_2 Eq. and Percent)

Source	2010 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Mineral Soil C Stocks: Land Converted to Cropland, Tier 3 Inventory Methodology	17.3				
Mineral Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	1.5	0.8	2.4	49	(54)
Organic Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	1.1	0.3	2.2	71	(94)
Combined Uncertainty for Flux associated with Soil Carbon Stock Change in Land Converted to Cropland	**20.0**				

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review. Uncertainty estimates will also be finalized during public review.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. 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) use of the DAYCENT biogeochemical model to estimate soil organic C stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; 4) extension of the tillage activity dataset with statistics from Conservation Technology and Information Center (CTIC 2004); and 5) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). *The influence of these changes on the time series is still being evaluated, but more information will be available after public review.*

QA/QC and Verification

See QA/QC and Verification section under *Cropland Remaining Cropland.*

Planned Improvements

The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties related to the structure of the DAYCENT model for *Land Converted to Cropland,* but this is a planned improvement. This improvement will produce a more rigorous assessment of uncertainty. In addition, 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. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.6. Grassland Remaining Grassland (IPCC Source Category 5C1)

Grassland Remaining Grassland includes all grassland in an inventory year that had been grassland for the previous 20 years[217] according to the USDA NRI land use survey (USDA-NRCS 2009). The Inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not address changes in C stocks for grasslands on federal lands, leading to a discrepancy between the total amount of managed area in *Grassland Remaining Grassland* (see Section 7.1) and the grassland area included in the Inventory. While federal grasslands probably have minimal changes in land management and C stocks, plans are being made to further evaluate and potentially include these areas in future C inventories.

Background on agricultural C stock changes is provided in the *Cropland Remaining Cropland* section and will only be summarized here for *Grassland Remaining Grassland.* Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared to soils. IPCC (2006) recommends reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[218]

Land-use and management of mineral soils in *Grassland Remaining Grassland* increased soil C, while organic soils lost relatively small amounts of C in each year 1990 through 2010. Due to the pattern for mineral soils, the overall trend was a gain in soil C over the time series although the rates varied from year to year, with a net removal of 2.4 Tg CO_2 Eq. (0.7 Tg C) in 2010. There was considerable variation over the time series driven by variability in weather patterns and associated interaction with land management activity. The change rates on per hectare basis were small, however, even in the years with larger total changes in stocks. Overall, flux rates declined by 17.3 Tg CO_2 Eq. (4.7 Tg C) when comparing the net change in soil C from 1990 and 2010.

Table 7-31: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg CO_2 Eq.)

Soil Type	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Mineral Soils	(23.1)		(20.8)	(45.0)	(5.7)	(5.5)	(5.4)	(5.2)
Organic Soils	3.4		2.8	2.8	2.8	2.8	2.8	2.8
Total Net Flux	**(19.7)**		**(18.0)**	**(42.2)**	**(2.9)**	**(2.8)**	**(2.6)**	**(2.4)**

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review.

Table 7-32: Net CO_2 Flux from Soil C Stock Changes in Grassland Remaining Grassland (Tg C)

Soil Type	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Mineral Soils	(6.3)		(5.7)	(12.3)	(1.6)	(1.5)	(1.5)	(1.4)

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[217] 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.

[218] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Organic Soils	0.9		0.8	0.8	0.8	0.8	0.8	(0.8)
Total Net Flux	**(5.4)**		**(4.9)**	**(11.5)**	**(0.8)**	**(0.8)**	**(0.7)**	**(0.7)**

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review.

Figure 7-9: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2010, *Grassland Remaining Grassland* [Maps will be provided in public review version]

Figure 7-10: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2010, *Grassland Remaining Grassland* [Maps will be provided in public review version]

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils for *Grassland Remaining Grassland*. 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 3.13.

Soil C stock changes were estimated for *Grassland Remaining Grassland* according to land-use histories recorded in the 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. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2007. 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. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach 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 soil organic C stocks and stock changes for *Grassland Remaining Grassland* were estimated using the DAYCENT biogeochemical 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 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 National Resources Inventory (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 Annex 3.13 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.

The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems based on methods described in the Manure Management, Section 6.2, and Annex 3.10. Manure N deposition from grazing animals (i.e., PRP manure) was an input to the DAYCENT model (see Annex 3.10), and included approximately 91 percent of total PRP manure (the remainder is deposited on federal lands, which are currently 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 2010 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years. See the Tier 3 methods in *Cropland Remaining Cropland* section for additional discussion on the Tier 3 methodology 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 (see *Cropland Remaining Cropland* Tier 2 methods section and Annex 3.13 for additional information).

Additional Mineral C Stock Change Calculations

Annual C flux estimates for mineral soils between 1990 and 2010 were adjusted to account for additional C stock changes associated with sewage sludge amendments using a Tier 2 method. 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 an EPA report (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. 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 assumed to rarely 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 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 3.13 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 (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Grassland Remaining Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2009). The annual emissions estimated for 1992 was applied to 1990 through 1992; annual emissions estimated for 1997 was applied to 1993 through 1997; annual emissions estimated for 2002 was applied to 1998 through 2002; and annual emissions estimated for 2007 was applied to 2003 through 2010.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 7-33 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 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component 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 is currently not available, but will be provided after public review.

Table 7-33: Tier 2 Quantitative Uncertainty Estimates for C Stock Changes occurring within *Grassland Remaining Grassland* (Tg CO_2 Eq. and Percent)

Source	2010 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	(4.1)				

Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	0.1	+	0.2	86	(110)
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Sewage Sludge Amendments)	(1.2)	(1.9)	(0.6)	(50)	50
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	2.8	1.4	4.6	48	(65)
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Grassland Remaining Grassland	**(2.4)**				

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review. Uncertainty estimates will also be finalized during public review.

+ Emissions are less than 0.1 Tg CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. 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) use of the DAYCENT biogeochemical model to estimate soil organic C stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; and 4) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). *The influence of these changes on the time series is still being evaluated, but more information will be available after public review.*

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. A minor error was found in the post-processing results to compute the final totals, which was corrected. *The quality control measures are ongoing and will be finalized with inventory estimates after public review.*

Planned Improvements

An automated quality assurance/quality control system is currently under development for the Tier 3 method that is used to estimate the majority of emissions associated with this source category. Currently, quality control is conducted by manual graphing and queries to determine if values are outside of an expected range. The new system will automatically create graphs, maps and conduct range checking to improve efficiency in this important step for the inventory analysis. This development will ensure a more thorough review of the inventory results.

7.7. Land Converted to Grassland (IPCC Source Category 5C2)

Land Converted to Grassland includes all grassland in an inventory year that had been in another land use at any point during the previous 20 years[219] according to the USDA NRI land-use survey (USDA-NRCS 2009). Consequently, lands are retained in this category for 20 years as recommended by IPCC (2006) unless there is another land use change. The Inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not address changes in C stocks for grasslands on federal lands, leading to a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Section 7.1) and the grassland area included in the Inventory. It is important to note that plans are being made to include these areas in future C

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[219] 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.

inventories.

Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Grassland.* Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. IPCC (2006) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[220]

Land-use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks from 1990 through 2010, which was largely due to annual cropland conversion to pasture (see Table 7-34 and Table 7-35). For example, the stock change rates were estimated to remove 6.8 Tg CO_2 Eq. (1.8 Tg C) and 11.4 Tg CO_2 Eq. (3.1 Tg C) from mineral soils in 1990 and 2010, respectively. Drainage of organic soils for grazing management led to losses varying from 0.4 to 0.8 Tg CO_2 Eq. yr^{-1} (0.1 to 0.2 Tg C).

Table 7-34: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg CO_2 Eq.)

Soil Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Mineral Soils[a]	(6.8)	(12.5)	(13.0)	(11.7)	(11.6)	(11.5)	(11.4)
Organic Soils	0.4	0.8	0.8	0.8	0.8	0.8	0.8
Total Net Flux	**(6.3)**	**(11.7)**	**(12.2)**	**(10.9)**	**(10.8)**	**(10.7)**	**(10.7)**

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review.

Table 7-35: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg C)

Soil Type	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Mineral Soils[a]	(1.8)	(3.4)	(3.5)	(3.2)	(3.2)	(3.1)	(3.1)
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Total Net Flux	**(1.7)**	**(3.2)**	**(3.3)**	**(3.0)**	**(3.0)**	**(2.9)**	**(2.9)**

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review.

Figure 7-11: Total Net Annual CO_2 Flux for Mineral Soils under Agricultural Management within States, 2010, *Land Converted to Grassland* [Maps will be provided in public review version]

Figure 7-12: Total Net Annual CO_2 Flux for Organic Soils under Agricultural Management within States, 2010, *Land Converted to Grassland* [Maps will be provided in public review version]

Methodology

This section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral soils for *Land Converted to Grassland.* Biomass C stock changes are not explicitly included in this category but losses of associated with conversion of forest to grassland are included in the *Forest Land Remaining Forest Land* section. 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 3.13.

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[220] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Soil C stock changes were estimated for *Land Converted to Grassland* according to land-use histories recorded in the 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. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2007. NRI points were classified as *Land Converted to Grassland* in a given year between 1990 and 2009 if the land use was grassland, but had been another use in the previous 20 years. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland typically includes extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach 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, perennial/horticultural crops, and rice; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.[221] A Tier 2 approach was also used to estimate additional changes in mineral soil C stocks due to sewage sludge amendments. However, stock changes associated with sewage sludge amendments are reported in the *Grassland Remaining Grassland* section.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical 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 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 Century simulations as recorded in the NRI survey, 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 *Grassland Remaining Grassland* Tier 3 methods section and Annex 3.13 for additional information).

Tier 2 Approach

The Tier 2 approach used for *Land Converted to Grassland* on mineral soils is the same as described for *Cropland Remaining Cropland* (See *Cropland Remaining Cropland* Tier 2 Approach and Annex 3.13 for additional information).

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 (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Land Converted to Grassland* areas from the *1997 National Resources Inventory* (USDA-NRCS 2009). The annual emissions estimated for 1992 was applied to 1990 through 1992; annual emissions estimated for 1997 was applied to 1993 through 1997; annual emissions estimated for 2002 was applied to 1998 through 2002; and annual emissions estimated for 2007 was applied to 2003 through 2010.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described in *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty or annual C emission estimates from drained organic soils in *Land Converted to Grassland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining*

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[221] 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).

Cropland section.

Uncertainty estimates are presented in Table 7-36 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 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component 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 is currently not available, but will be provided after public review.

Table 7-36: Tier 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (Tg CO_2 Eq. and Percent)

Source	**2010 Flux Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Flux Estimate**			
		(Tg CO_2 Eq.)		**(%)**	
		Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Mineral Soil C Stocks: Land Converted to Grassland, Tier 3 Inventory Methodology	(8.9)				
Mineral Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	(2.5)	(3.7)	(1.4)	(48)	44
Organic Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	0.8	0.4	1.4	51	(72)
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stocks in Land Converted to Grassland	**(10.7)**				

Note: Preliminary estimates that will be finalized after quality control measures are completed during public review. Uncertainty estimates will also be finalized during public review.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2010. 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) use of the DAYCENT biogeochemical model to estimate soil organic C stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; and 4) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). *The influence of these changes on the time series is still being evaluated, but more information will be available after public review.*

QA/QC and Verification

See the QA/QC and Verification section under *Grassland Remaining Grassland.*

Planned Improvements

The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties related to the structure of the DAYCENT model for *Land Converted to Cropland,* but this is a planned improvement. This improvement will produce a more rigorous assessment of uncertainty. In addition, 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. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.8. Wetlands Remaining Wetlands

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., draining, and clearing surface biomass), 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 greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al., 2004 as cited in IPCC 2006); however, CH_4 emissions are assumed to be insignificant under Tier 1 (IPCC, 2006). N_2O emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions, and at present no methodology is provided by IPCC (2006) to estimate greenhouse gas emissions or removals from restored peatlands. This inventory estimates both CO_2 and N_2O emissions from *Peatlands Remaining Peatlands* in accordance with Tier 1 IPCC (2006) guidelines.

CO_2 and N_2O Emissions from *Peatlands Remaining Peatlands*

IPCC (2006) recommends reporting CO_2 and N_2O emissions from lands undergoing active peat extraction (i.e., *Peatlands Remaining Peatlands*) as part of the estimate for emissions from managed wetlands. Peatlands occur in wetland areas 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 and wetlands in states further south. 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) recommends 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 emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat. 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.

Off-site CO_2 emissions from managed peatlands occur from 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 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 horticultural purposes.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 1.098 Tg CO_2 Eq. in 2010 (see Table 7-37) comprising 0.983 Tg CO_2 Eq. (983 Gg) of CO_2 and 0.005 Tg CO_2 Eq. (0.016 Gg) of N_2O. Total emissions in 2010 were about 11 percent smaller than total emissions in 2009, with the decrease due to the decrease in peat production reported in Alaska in 2010.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO_2 Eq. across the time series with a decreasing trend from 1990 until 1994 followed by an increasing trend through 2000. After 2000, emissions generally increased until 2006 and then decreased until 2009, when the trend reversed. Emissions in 2010 represent a slight decline from emissions in 2009. CO_2 emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO_2 across the time series, and these emissions drive the trends in total emissions. N_2O emissions remained close to zero across the time series, with a decreasing trend from 1990 until 1995 followed by an increasing trend through 2002. N_2O emissions decreased between 2000 and 2008, followed by a leveling off since 2008.

Table 7-37: Emissions from *Peatlands Remaining Peatlands* (Tg CO_2 Eq.)

Gas	1990		2005	2006	2007	2008	2009	2010
CO_2	1.0		1.1	0.9	1.0	1.0	1.1	1.0
N_2O	+		+	+	+	+	+	+
Total	**1.0**		**1.1**	**0.9**	**1.0**	**1.0**	**1.1**	**1.0**

+ Less than 0.01 Tg 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).

Table 7-38: Emissions from *Peatlands Remaining Peatlands* (Gg)

Gas	1990		2005	2006	2007	2008	2009	2010
CO_2	1,033		1,079	879	1,012	992	1,089	983
N_2O	+		+	+	+	+	+	+

+ Less than 0.05 Gg

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).

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 7-39) 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 carbon 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 1991–2011). 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. USGS estimated data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from Alaska's annual Mineral Industry Reports (Szumigala et al. 2010). Similar to the U.S. Geological Survey, Alaska's Mineral Industry Report methodology solicits voluntary reporting of peat production from producers. 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 (USGS 1991-2011). 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 7-40). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific carbon fraction conversion factors from IPCC (2006).[222]

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. Therefore, off-site CO_2 emissions from the use of all horticultural peat within the United States are not accounted for using the Tier 1 approach. The United States has increasingly imported peat from Canada for horticultural purposes; from 2006 to 2009, imports of sphagnum moss (nutrient-poor) peat from Canada represented 97 percent of total U.S. peat imports (USGS 2011a). 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 7-39: Peat Production of Lower 48 States (in thousands of Metric Tons)

Type of Deposit	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Nutrient-Rich	595.1	657.6	529.0	581.0	559.7	560.3	563.0
Nutrient-Poor	55.4	27.4	22.0	54.0	55.4	48.7	49.0
Total Production	**692.0**	**685.0**	**551.0**	**635.0**	**615.0**	**609.0**	**612.0**

Source: United States Geological Survey (USGS) (1991–2011)..

Table 7-40: Peat Production of Alaska (in thousands of Cubic Meters)

	1990	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Total Production	**49.7**	**47.8**	**50.8**	**52.3**	**64.1**	**183.9**	**78.2**

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2011) Alaska's Mineral Industry Report (1997–2010).

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emissions 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[223] can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006). 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 appropriate nutrient-rich or nutrient-poor IPCC (2006) 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 carbon stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in carbon stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006).

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[222] 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).

[223] 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).

On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emissions 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 (2006).

Uncertainty

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 Alaskan reported production data was assumed to be the same as the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the Alaska Department of Natural Resources 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) 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 emissions factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed. The uncertainty values surrounding the carbon fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed. Based on these values and distributions, a Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 and N_2O emissions from *Peatlands Remaining Peatlands*. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-41. CO_2 emissions from *Peatlands Remaining Peatlands* in 2010 were estimated to be between 0.7 and 1.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 33 percent below to 38 percent above the 2010 emission estimate of 1.0 Tg CO_2 Eq. N_2O emissions from *Peatlands Remaining Peatlands* in 2010 were estimated to be between 0.001 and 0.007 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 74 percent below to 42 percent above the 2010 emission estimate of 0.005 Tg CO_2 Eq.

Table 7-41: Tier-2 Quantitative Uncertainty Estimates for CO_2 Emissions from *Peatlands Remaining Peatlands*

Source	**Gas**	**2010 Emissions Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emissions Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Peatlands Remaining Peatlands	CO_2	1.0	0.7	1.4	−33%	38%
	N_2O	+	+	+	−74%	42%

+ Does not exceed 0.01 Tg CO_2 Eq. or 0.5 Gg.

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

QA/QC and Verification

A QA/QC analysis was performed 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 represents the fourth inventory report in which emissions from *Peatlands Remaining Peatlands* are included. The inventory estimates for 2009 have been updated to incorporate new information on the proportion of rich and poor peat soil, and the bulk density of peat types in 2009. These data are from the advance release of the *2009 Mineral Yearbook: Peat* (USGS 2011b), which was released too late to be fully incorporated into last year's inventory estimates, Updating these 2009 input values resulted in less than a 1 percent decrease compared to the previous 2009 emission estimate.

Planned Improvements

In order to further improve estimates of CO_2 and N_2O 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.

7.9. Settlements Remaining Settlements

Changes in Carbon Stocks in Urban Trees (IPCC Source Category 5E1)

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 4 percent of the United States (Nowak et al. 2005). With an average tree canopy cover of 27 percent, urban areas account for approximately 3 percent of total tree cover in the continental United States (Nowak et al. 2001). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 77.5 Tg CO_2 Eq. (21.1 Tg C) over the period from 1990 through 2010. Net C flux from urban trees in 2010 was estimated to be −98.0 Tg CO_2 Eq. (−26.7 Tg C). Annual estimates of CO_2 flux (Table 7-43) were developed based on periodic (1990 and 2000) 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 19 percent over the 1990 through 2010 time series—i.e., the Census urban area is a subset of the *Settlements* area.

In 2010, urban area was about 7 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 72 percent between 1990 and 2010 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 carbon stocks in urban trees for *Settlements* areas, but are representative of changes in carbon 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 carbon stocks in urban trees in all *Settlements* areas—i.e., the changes in carbon stocks in urban trees presented in this chapter are a subset of the changes in carbon stocks in urban trees in all *Settlements* areas.

Net C flux from urban trees is proportionately greater on an area basis than that of forests. This trend is primarily the result of different net growth rates in urban areas versus forests—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 7-42: Net C Flux from Urban Trees (Tg CO_2 Eq. and Tg C)

Year	Tg CO_2 Eq.	Tg C
1990	(57.1)	(15.6)
2005	(87.8)	(23.9)
2006	(89.8)	(24.5)
2007	(91.9)	(25.1)
2008	(93.9)	(25.6)
2009	(95.9)	(26.2)
2010	(98.0)	(26.7)

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 and Crane (2002) and Nowak (1994). In general, the methodology used by Nowak and Crane (2002) to estimate net C sequestration in urban trees followed three steps. First, field data from 14 cities were used to generate allometric estimates of biomass from measured tree dimensions. Second, estimates of tree growth and biomass increment were generated from published literature and adjusted for tree condition and land-use class to generate estimates of gross C sequestration in urban trees. 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 these cities, in units of carbon sequestered per unit area of tree cover, were used to estimate urban forest C sequestration in the U.S. by using urban area estimates from U.S. Census data and urban tree cover estimates from remote sensing data, an approach consistent with Nowak and Crane (2002).

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. Annual changes in net C flux from urban trees are based solely on changes in total urban area in the United States.

In order to generate the allometric relationships between tree dimensions and tree biomass, Nowak and Crane (2002) and Nowak (1994, 2007c, 2009) collected field measurements in a number of U.S. cities between 1989 and 2002. For a sample of trees in each of the cities in Table 7-44, 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 carbon 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 was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates (Nowak 2011a).

Most of the field data used to develop the methodology of Nowak et al. 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. 2007a).

Gross C emissions result from tree death and removals. Estimates of gross 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 field data for 13 of the 14 cities are described in Nowak and Crane (2002), Nowak et al. (2007a), and references cited therein. Data for the remaining city, Chicago, were taken from unpublished results (Nowak 2009). 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). A root-to-shoot ratio of 0.26 was taken from Cairns et al. (1997), and species- or genus-specific moisture contents were taken from various literature sources (see Nowak 1994). Tree growth rates were taken from existing literature. Average diameter growth was based on the following sources: estimates for trees in forest stands came from Smith and Shifley (1984); estimates for trees on land uses with a park-like structure came from deVries (1987); and estimates for more open-grown trees came from Nowak (1994). Formulas from Fleming (1988) formed the basis for average height growth calculations. As described above, growth rates were adjusted to account for tree condition. Growth factors for Atlanta, Boston, Freehold, Jersey City, Moorestown, New York, Philadelphia, and Woodbridge were adjusted based on the typical growth conditions of different land-use categories (e.g., forest stands, park-like stands). Growth factors for the more recent studies in Baltimore, Chicago, Minneapolis, San Francisco, Syracuse, and Washington were adjusted using an updated methodology based on the condition of each individual tree, which is determined using tree competition factors (depending on whether it is open grown or suppressed) (Nowak 2007b). 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 and Crane 2002).

Estimates of gross and net sequestration rates for each of the 14 cities (Table 7-44) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of national urban area and urban tree cover data to calculate national annual net C sequestration by urban trees for the United States. This method was described in Nowak and Crane (2002) and has been modified to incorporate U.S. Census data.

Specifically, urban area estimates were based on 1990 and 2000 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. Urban land area increased by approximately 36 percent from 1990 to 2000; 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 both 1990 and 2000 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 carbon stocks between urban forest and non-urban forest(see Planned Improvements below). Specifically, tree canopy cover of U.S. urban areas was estimated by Nowak et al. (2001) to be 27 percent, assessed across Census-delineated urbanized areas, urban places, and places containing urbanized area. This canopy cover percentage is multiplied by the urban area estimated for each year to produce an estimate of national urban tree cover area.

Net annual C sequestration estimates were derived for the 14 cities by subtracting the gross annual emission estimates from the gross annual sequestration estimates. The gross and net annual C sequestration values for each city were divided by each city’s area of tree cover to determine the average annual sequestration rates per unit of tree area for each city. The median value for gross sequestration per unit area of tree cover (0.29 kg C/m^2-yr) was then multiplied by the estimate of national urban tree cover area to estimate national annual gross sequestration, per the methods of Nowak and Crane (2002). To estimate national annual net sequestration, the estimate of national annual gross sequestration was multiplied by the average of the ratios of net to gross sequestration (0.72) for those cities that had both estimates. The urban tree cover estimates for each of the 14 cities and the United States were obtained from Dwyer et al. (2000), Nowak et al. (2002), Nowak (2007a), and Nowak (2009). The urban area estimates were taken from Nowak et al. (2005).

Table 7-43: C Stocks (Metric Tons C), 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 14 U.S. Cities

City	Carbon Stocks	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
Atlanta, GA	1,219,256	42,093	32,169	36.7%	0.34	0.26	0.76
Baltimore, MD	541,589	14,696	9,261	21.0%	0.35	0.22	0.63
Boston, MA	289,392	9,525	6,966	22.3%	0.30	0.22	0.73
Chicago, IL	649,000	22,800	16,100	17.2%	0.22	0.16	0.71
Freehold, NJ	18,144	494	318	34.4%	0.28	0.18	0.64
Jersey City, NJ	19,051	807	577	11.5%	0.18	0.13	0.71
Minneapolis, MN	226,796	8,074	4,265	26.4%	0.20	0.11	0.53
Moorestown, NJ	106,141	3,411	2,577	28.0%	0.32	0.24	0.76
New York, NY	1,224,699	38,374	20,786	20.9%	0.23	0.12	0.54
Philadelphia, PA	480,808	14,606	10,530	15.7%	0.27	0.20	0.72
San Francisco, CA	175,994	4,627	4,152	11.9%	0.33	0.29	0.90
Syracuse, NY	156,943	4,917	4,270	23.1%	0.33	0.29	0.87
Washington, DC	477,179	14,696	11,661	28.6%	0.32	0.26	0.79
Woodbridge, NJ	145,150	5,044	3,663	29.5%	0.28	0.21	0.73
					Median: 0.29		**Mean:** 0.72

NA = not analyzed.
Sources: Nowak and Crane (2002), Nowak (2007a,c), and Nowak (2009).

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 14 U.S. cities. A 10 percent uncertainty was associated with urban area estimates while a 5 percent uncertainty was associated with percent urban tree coverage. Both of these uncertainty estimates were based on expert judgment. Uncertainty associated with estimates of gross and net C sequestration for each of the 14 U.S. cities was based on standard error estimates for each of the city-level sequestration estimates reported by Nowak (2007c) and Nowak (2009). These estimates are based on field data collected in each of the 14 U.S. cities, 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 (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-44. The net C flux from changes in C stocks in urban trees in 2010 was estimated to be between −120.1 and −78.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 23 percent below and 20 percent above the 2010 flux estimate of −98.0 Tg CO_2 Eq.

Table 7-44: Tier 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Urban Trees	CO_2	(98.0)	(120.1)	(78.0)	23%	−20%

Note: Parentheses indicate negative values or net sequestration.

Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The net C flux resulting from urban trees was predominately calculated using estimates of gross and net C sequestration estimates for urban trees and urban tree coverage area published in the literature. The validity of these data for their use in this section of the inventory was evaluated through correspondence established with an author of the papers. Through this correspondence, the methods used to collect the urban tree sequestration and area data were further clarified and the use of these data in the inventory was reviewed and validated (Nowak 2002a, 2007b, 2011a).

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 (2012, in preparation) estimates that 13.7 percent of urban land is measured by the forest inventory plots, and could be responsible for up to 87 Tg C of overlap.

Urban forest data for 28 cities are expected in the near future, including updated data for cities currently included in the estimates (Nowak 2012, in preparation). The use of these data will refine the estimated median Gross Annual Sequestration per Area of Tree Cover value.

The U.S. Census Bureau expects to publish data on urban areas from the 2010 Census in early 2013 (Allen 2011). These data would allow for refinement of the urban area time series. Revisions to urban area time series will result in revisions to all years' C flux estimates.

A revised average tree canopy cover percentage of 33.5 percent for U.S. urban areas has also been established, and is in preparation for publication (Nowak 2012, in preparation). Revisions to tree cover percentage will result in revisions to all years' C flux estimates. Furthermore, urban tree cover data specific to six states has also been developed (Nowak 2012, in preparation). It may be possible to develop and use a set of state-specific sequestration rates for estimating regional C flux estimates.

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.

Direct N_2O Fluxes from Settlement Soils (IPCC Source Category 5E1)

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. In 2010, N_2O emissions from settlement soils were 1.4 Tg CO_2 Eq. (4.5 Gg). There was an overall increase of 43 percent over the period from 1990 through 2010 due to a general increase in the application of synthetic N fertilizers to 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 7-45.

Table 7-45: Direct N_2O Fluxes from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Gg N_2O)

Year	Tg CO_2 Eq.	Gg
1990	1.0	3.2
2005	1.5	4.7
2006	1.5	4.8

2007	1.6	5.1
2008	1.5	4.7
2009	1.4	4.4
2010	1.4	4.5

Note: These estimates include direct N_2O emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

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 of sewage sludge (see Annex 3.11 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 2008 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 3.11 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). The volatilized and leached/runoff N fractions for settlements, calculated with the IPCC default volatilization factors (10 or 20 percent, respectively, for synthetic or organic N fertilizers) and leaching/runoff factor for wet areas (30 percent), were included with indirect emissions, as reported in the N_2O Emissions from Agricultural Soil Management source category of the Agriculture chapter (consistent with reporting guidance that all indirect emissions are included in the Agricultural Soil Management source category).

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[224] of ±50 percent. 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. Uncertainty in the emission factors was provided by the IPCC (2006).

Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables

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[224] No uncertainty is provided with the USGS fertilizer consumption data (Ruddy et al. 2006) so a conservative ±50% was used in the analysis.

were directly applied to the 2010 emission estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-46. N_2O emissions from soils in Settlements Remaining Settlements in 2010 were estimated to be between 0.7 and 3.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2010 emission estimate of 1.4 Tg CO_2 Eq.

Table 7-46: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emissions (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Settlements Remaining Settlements: N_2O Fluxes from Soils	N_2O	1.4	0.7	3.7	-49%	163%

Note: This estimate includes direct N_2O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

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.

7.10. Land Converted to Settlements (Source Category 5E2)

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.

7.11. Other (IPCC Source Category 5G)

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. 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 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. C 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 2011; Schneider 2007, 2008). 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 5 percent decrease in the tonnage 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 2010. The net effect of the reduction in generation and the increase in composting is a 54 percent decrease in the quantity of yard trimmings disposed in landfills since 1990.

Food scrap generation has grown by 46 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 80 percent in 2010, the tonnage disposed in landfills has increased considerably (by 42 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 carbon storage from 24.2 Tg CO_2 Eq. in 1990 to 13.3 Tg CO_2 Eq. in 2010 (Table 7-47 and Table 7-48).

Table 7-47: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO_2 Eq.)

Carbon Pool	1990	2005	2006	2007	2008	2009	2010
Yard Trimmings	**(21.0)**	**(7.3)**	**(7.4)**	**(7.0)**	**(7.0)**	**(8.5)**	**(9.3)**
Grass	(1.8)	(0.6)	(0.6)	(0.6)	(0.6)	(0.8)	(0.9)
Leaves	(9.0)	(3.3)	(3.4)	(3.2)	(3.2)	(3.9)	(4.2)
Branches	(10.2)	(3.4)	(3.4)	(3.2)	(3.1)	(3.8)	(4.1)
Food Scraps	**(3.2)**	**(4.3)**	**(3.5)**	**(3.9)**	**(3.9)**	**(4.2)**	**(4.1)**
Total Net Flux	**(24.2)**	**(11.6)**	**(11.0)**	**(10.9)**	**(10.9)**	**(12.7)**	**(13.3)**

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

Table 7-48: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	1990	2005	2006	2007	2008	2009	2010
Yard Trimmings	**(5.7)**	**(2.0)**	**(2.0)**	**(1.9)**	**(1.9)**	**(2.3)**	**(2.5)**
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.3)
Leaves	(2.5)	(0.9)	(0.9)	(0.9)	(0.9)	(1.1)	(1.1)
Branches	(2.8)	(0.9)	(0.9)	(0.9)	(0.9)	(1.0)	(1.1)
Food Scraps	**(0.9)**	**(1.2)**	**(1.0)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**
Total Net Flux	**(6.6)**	**(3.2)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.5)**	**(3.6)**

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

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). C 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 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 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: Tables and Figures for 2010* (EPA 2011), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, and 2007 through 2010. To provide data for some of the missing years, detailed backup data were obtained from Schneider (2007, 2008). Remaining years in the time series for which data were not provided were estimated using linear interpolation. The EPA (2011) report does not subdivide discards of individual materials into volumes landfilled and combusted, although it provides an estimate of the proportion of overall waste stream discards managed in landfills[225] and combustors with energy recovery (i.e., ranging from 100 percent and 0 percent, respectively, in 1960 to 81 percent and 19 percent in 2000); 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 7-49).

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 a "seed" containing 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 "CS" in Table 7-49).

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, 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 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.

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 yr^{-1}, respectively.

De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 yr^{-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 yr^{-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 7-49.

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:

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[225] EPA (2011) 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.

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

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 in landfills in year n (metric tons, wet weight),
n = Year in which the waste was disposed (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 (2010). 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 2010, the total food scraps C originally disposed 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 in subsequent years (1961 through 2010), the total landfill C from food scraps in 2010 was 37.0 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 2010, yielding a value of 250.7 million metric tons (as shown in Table 7-50). 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 7-48) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2010 shown in Table 7-48 (3.6 Tg C) is equal to the stock in 2010 (250.7 Tg C) minus the stock in 2009 (247.0 Tg C).

The C stocks calculated through this procedure are shown in Table 7-50.

Table 7-49: Moisture Content (%), C Storage Factor, Proportion of Initial C Sequestered (%), Initial C Content (%), and Decay Rate (year^{-1}) for Landfilled Yard Trimmings and Food Scraps in Landfills

	Yard Trimmings			**Food Scraps**
Variable	**Grass**	**Leaves**	**Branches**	
Moisture Content (% H_2O)	70	30	10	70
CS, 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 7-50: C Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	**1990**		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Yard Trimmings	**155.8**		**202.9**	**205.0**	**206.9**	**208.8**	**211.1**	**213.6**
Branches	74.6		97.5	98.5	99.3	100.2	101.2	102.3
Leaves	66.7		87.3	88.3	89.2	90.0	91.1	92.2
Grass	14.5		18.1	18.2	18.4	18.6	18.8	19.0
Food Scraps	**21.3**		**31.7**	**32.7**	**33.7**	**34.8**	**35.9**	**37.0**

Total Carbon Stocks	**177.2**	▨	**234.7**	**237.7**	**240.6**	**243.6**	**247.0**	**250.7**

Note: Totals may not sum due to independent rounding.

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 (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-51. Total yard trimmings and food scraps CO_2 flux in 2010 was estimated to be between −20.85 and −6.25 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 57 percent below to 53 percent above the 2010 flux estimate of −13.32 Tg CO_2 Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

Table 7-51: Tier 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Flux Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Flux Estimate**[a] **(Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Yard Trimmings and Food Scraps	CO_2	(13.3)	(20.9)	(6.3)	−57%	+53%

[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 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

The current Inventory has been revised relative to the previous document. Input data were updated for the years: 1990, 2000, 2005, and 2007 through 2010 based on the updated values reported in *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2010* (EPA 2011). As a result, C storage estimates for those years were revised relative to the previous inventory. While data inputs for intervening years in the time series were not revised, overall C storage in any given year is dependent on the previous year's storage (as shown in the second equation above), and so C storage estimates for those years were also revised. These revisions resulted in an annual average decrease in C stored in landfills of 0.1 percent across the time series.

Planned Improvements

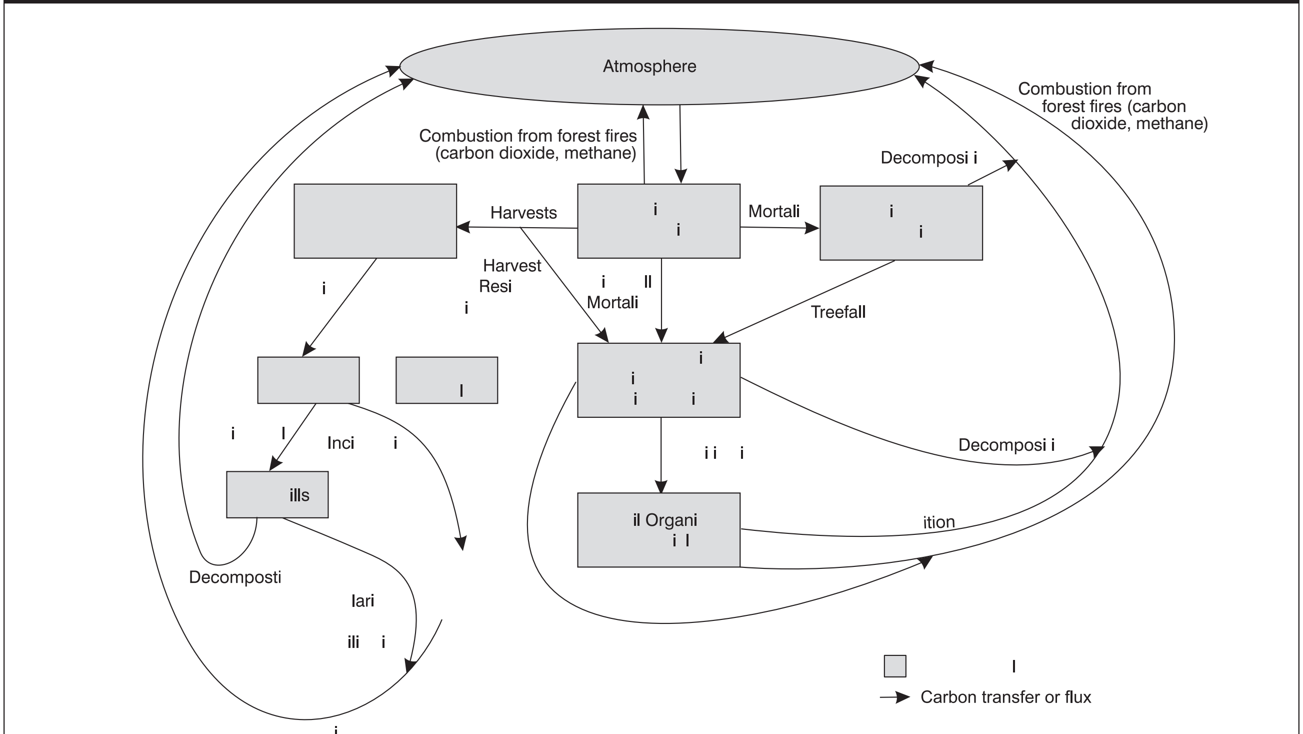
Future work is planned to evaluate the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH_4 emissions described in the Waste chapter. For example, the Waste chapter does not distinguish landfill CH_4 emissions from yard trimmings and food scraps separately from landfill CH_4 emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps.

To be provided:

Figure 7-1. Percent of Total Land Area in the General Land Use Categories for 2010

Figure 7-2

Forest Sector Carbon Pools and Flows



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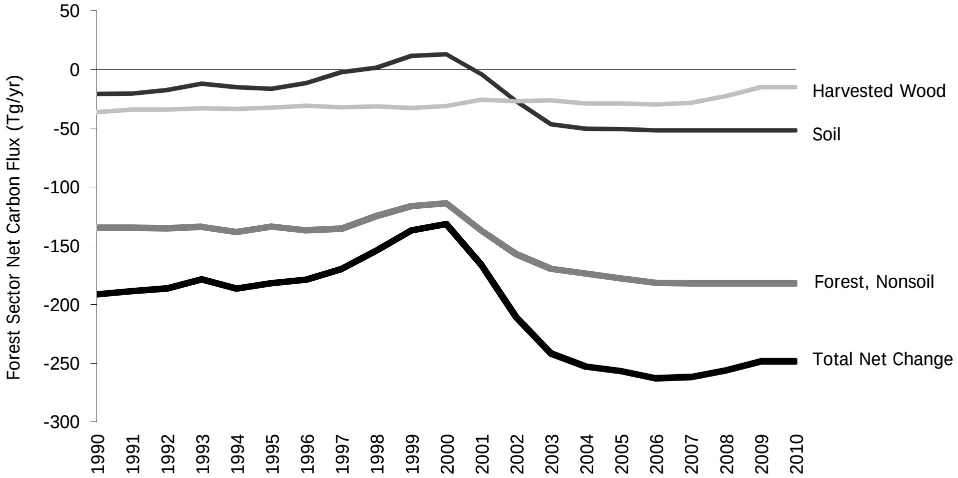
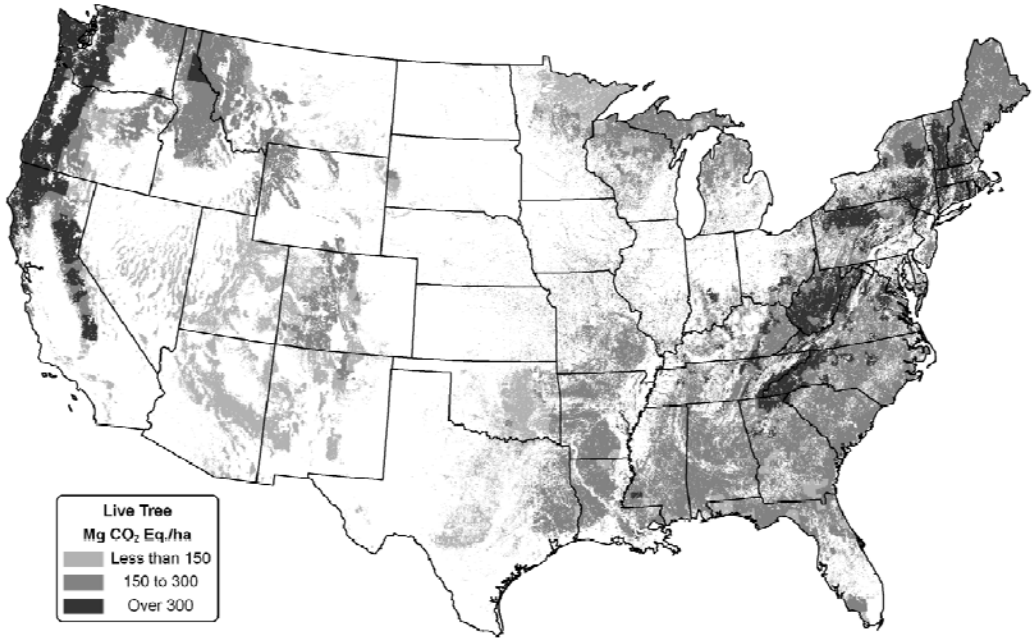


Figure 7-3: Estimates of Net Annual Changes in C Stocks for Major C Pools

Figure 7-4

Average C Density in the Forest Tree Pool in the Conterminous United States, 2010



To be provided:

Figure 7-5: Total Net Annual CO2 Flux for Mineral Soils under Agricultural Management within States, 2010: Cropland Remaining Cropland

To be provided:

Figure 7-6: Total Net Annual CO2 Flux for Organic Soils under Agricultural Management within States, 2010: Cropland Remaining Cropland

To be provided:

Figure 7-7: Total Net Annual CO2 Flux for Mineral Soils under Agricultural Management within States, 2010: Land Converted to Cropland

To be provided:

Figure 7-8: Total Net Annual CO2 Flux for Organic Soils under Agricultural Management within States, 2010: Land Converted to Cropland

To be provided:

Figure 7-9: Total Net Annual CO2 Flux for Mineral Soils under Agricultural Management within States, 2010: Grassland Remaining Grassland

To be provided:

Figure 7-10: Total Net Annual CO2 Flux for Organic Soils under Agricultural Management within States, 2010: Grassland Remaining Grassland

To be provided:

Figure 7-11: Total Net Annual CO2 Flux for Mineral Soils under Agricultural Management within States, 2010: Land Converted to Grassland

To be provided:

Figure 7-12: Total Net Annual CO2 Flux for Organic Soils under Agricultural Management within States, 2010: Land Converted to Grassland

8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills accounted for approximately 16.0 percent of total U.S. anthropogenic methane (CH_4) emissions in 2010, 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. methane 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 3 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 8-1 and Table 8-2.

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, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2010 resulted in 12.3 Tg CO_2 Eq. emissions, nearly half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3.

Figure 8-1: 2010 Waste Chapter Greenhouse Gas Sources

[BEGIN BOX]

Box 8-1: 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).[226] 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.[227] 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,[228] 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.

[END BOX]

Overall, in 2010, waste activities generated emissions of 132.5 Tg CO_2 Eq., or just under 2 percent of total U.S. greenhouse gas emissions.

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

[227] See http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5270.php.

[228] For example, see http://www.epa.gov/aboutepa/oswer.html.

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**163.9**	**130.8**	**130.0**	**130.0**	**131.4**	**129.3**	**125.8**
Landfills	147.7	112.7	111.7	111.7	113.1	111.2	107.8
Wastewater Treatment	15.9	16.5	16.7	16.6	16.6	16.5	16.3
Composting	0.3	1.6	1.6	1.7	1.7	1.6	1.6
N_2O	**3.8**	**6.4**	**6.5**	**6.7**	**6.8**	**6.7**	**6.8**
Domestic Wastewater Treatment	3.5	4.7	4.8	4.8	4.9	5.0	5.0
Composting	0.4	1.7	1.8	1.8	1.9	1.8	1.7
Total	**167.7**	**137.2**	**136.5**	**136.7**	**138.2**	**136.0**	**132.5**

Note: Totals may not sum due to independent rounding.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	2005	2006	2007	2008	2009	2010
CH_4	**7,805**	**6,228**	**6,189**	**6,191**	**6,258**	**6,157**	**5,988**
Landfills	7,032	5,367	5,320	5,320	5,386	5,295	5,135
Wastewater Treatment	758	785	794	791	792	787	779
Composting	15	75	75	79	80	75	75
N_2O	**12**	**21**	**21**	**22**	**22**	**22**	**22**
Domestic Wastewater Treatment	11	15	15	16	16	16	16
Composting	1	6	6	6	6	6	6

Note: Totals may not sum due to independent rounding.

[BEGIN BOX]

Box 8-2: Waste Data from the Greenhouse Gas Reporting Program

On October 30, 2009, the 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 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. For calendar year 2010, the first year in which data were reported, facilities in 29 categories provided in 40 CFR part 98 were required to report their 2010 emissions by the September 30, 2011 reporting deadline. This includes owners or operators of municipal solid waste (MSW) landfills, as defined in 40 CFR part 98, that accepted waste on or after January 1, 1980 and generate methane (CH_4) in amounts equivalent to 25,000 metric tons of carbon dioxide equivalent (CO_2 Eq) or more per year.

The GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective Planned Improvements section 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 the GHGRP are consistent with the IPCC methodologies, though for the 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 for source categories in the 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 source categories identified in the IPCC guidelines. Further information on the reporting categorization in GHGRP and specific data caveats associated with monitoring methods in the GHGRP can be accessed at: <http://www.ccdsupport.com/confluence/display/ghgp/Detailed+Description+of+Data+for+Certain+Sources+and+Processes>.

EPA presents the data collected by the 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. The GHGRP data publication tool can be accessed at:< http://ghgdata.epa.gov>.

Figure 8-x: 2010 Waste Facility Emissions, as Reported under the GHG Reporting Program

[END BOX]

8.1. Landfills (IPCC Source Category 6A1)

In 2010, landfill CH_4 emissions were approximately 107.8 Tg CO_2 Eq. (5,135 Gg of CH_4), representing the third largest source of CH_4 emissions in the United States, behind natural gas systems and enteric fermentation. Emissions from municipal solid waste (MSW) landfills, which received about 69 percent of the total solid waste generated in the United States, accounted for about 94 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,900 operational landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 (EPA 2010; *BioCycle* 2008, adjusted to include missing data from five states). While the number of landfills has decreased significantly over the past 20 years, from 6,326 in 1990 to 1,908 in 2009), the average landfill size has increased (EPA 2010).

After being placed in a landfill, waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These CH_4-producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Significant CH_4 production typically begins one or two years after waste disposal in a landfill and continues for 10 to 60 years or longer.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of waste in MSW landfills, which is related to total waste landfilled annually; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place, size, climate); (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 in landfills instead of being released into the atmosphere. From 1990 to 2010, net CH_4 emissions from landfills decreased by approximately 27 percent (see Table 8-3 and Table 8-4). This net CH_4 emissions decrease can be attributed to many factors, including changes in waste composition, an increase in the amount of landfill gas collected and combusted, a higher frequency of composting, and increased rates of recovery for degradable materials (e.g., paper and paperboard).

The estimated annual quantity of waste placed in MSW landfills increased from about 206 Tg in 1990 to 254 Tg in 2010, an increase of 23 percent (see Annex 3.14). Despite increased waste disposal, the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills have decreased by approximately 21 percent from 1990 to 2009 (EPA 2010). In addition, the amount of landfill gas collected and combusted has increased. In 1990, for example, approximately 960 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills, while in 2010, 7,627 Gg CH_4 was combusted, which represents a 5 percent increase in the quantity of CH_4 recovered and combusted from 2009 levels (see Annex 3.14). In 2010, an estimated 54 new landfill gas-to-energy (LFGTE) projects and 46 new flares began operation (EPA 2011).

Over the past 9 years, however, the net CH_4 emissions have fluctuated from year to year, but a slowly increasing trend has been observed. 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.

Over the next several years, the total amount of municipal solid waste generated is expected to increase as the U.S. population continues to grow. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of CH_4 that is recovered and either flared or used for energy purposes is expected to continue to increase as a result of 1996 federal regulations that require large municipal solid waste 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 use 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).

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	2000	2005	2006	2007	2008	2009	2010
MSW Landfills	172.6	206.9	241.2	247.6	252.9	256.8	260.4	264.0
Industrial Landfills	11.6	14.5	15.4	15.4	15.5	15.7	15.8	15.9
Recovered								
Gas-to-Energy	(13.4)	(50.2)	(55.9)	(58.2)	(61.9)	(66.2)	(74.4)	(79.8)
Flared	(6.7)	(47.8)	(75.5)	(80.7)	(82.4)	(80.6)	(78.3)	(80.3)
Oxidized[a]	(16.4)	(12.3)	(12.5)	(12.4)	(12.4)	(12.6)	(12.4)	(12.0)
Total	**147.7**	**111.1**	**112.7**	**111.7**	**111.7**	**113.1**	**111.2**	**107.8**

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

[a] Includes oxidation at both municipal and industrial landfills.

Table 8-4: CH_4 Emissions from Landfills (Gg)

Activity	1990	2000	2005	2006	2007	2008	2009	2010
MSW Landfills	8,219	9,854	11,486	11,790	12,041	12,227	12,401	12,574
Industrial Landfills	554	692	733	736	740	746	752	758
Recovered								
Gas-to-Energy	(640)	(2,390)	(2,662)	(2,773)	(2,946)	(3,152)	(3,543)	(3,802)
Flared	(321)	(2,278)	(3,593)	(3,842)	(3,923)	(3,837)	(3,726)	(3,825)
Oxidized[a]	(781)	(588)	(596)	(591)	(591)	(598)	(588)	(571)
Total	**7,032**	**5,290**	**5,367**	**5,320**	**5,320**	**5,386**	**5,295**	**5,135**

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

[a] Includes CH_4 oxidation at municipal and industrial landfills.

Methodology

CH_4 emissions from landfills were estimated as the CH_4 produced from municipal solid waste landfills, plus the CH_4 produced by industrial landfills, minus the CH_4 recovered and combusted, minus the CH_4 oxidized before being released into the atmosphere:

$$CH_{4,\text{Solid Waste}} = [CH_{4,\text{MSW}} + CH_{4,\text{Ind}} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$ = CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$ = CH_4 generation from municipal solid waste landfills,
$CH_{4,\text{Ind}}$ = CH_4 generation from industrial landfills,
R = CH_4 recovered and combusted, and
Ox = CH_4 oxidized from MSW and industrial landfills before release to the atmosphere.

The methodology for estimating CH_4 emissions from municipal solid waste landfills is based on the first order decay model described by the Intergovernmental Panel on Climate Change (IPCC 2006). Values for the CH_4 generation potential (L_0) and rate constant (k) 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 rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall. 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, and historical census data were used to account for the shift in population to more arid areas over time. A detailed description of the methodology used to estimate CH_4 emissions from landfills can be found in Annex 3.14.

National landfill waste generation and disposal data for 2007, 2009, and 2010 were extrapolated based on *BioCycle* data for 2008 and the U.S. Census population from 2010. Data for 1989 through 2008 were obtained from *BioCycle* (BioCycle 2006, 2008, and 2010). Because *BioCycle* 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 (2010) and national per capita solid waste generation from *BioCycle* (2010). 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 this 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). Please see Annex 3.14 for more details.

The estimated landfill gas recovered per year was based on updated sales data collected from vendors of flaring equipment (referred to as the flare vendor database), a database of landfill gas-to-energy (LFGTE) projects compiled by LMOP (EPA 2011), and a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007). The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double counting reductions. Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to 2010 was estimated.

The flare vendor database estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity while the EIA database uses landfill-specific measured gas flow. As the EIA database only includes data through 2006; 2007 to 2010 recovery for projects included in the EIA database were assumed to be the same as in 2006. This quantity likely underestimates flaring because these databases do not have information on all flares in operation. Additionally, the EIA and LMOP databases provided data on landfill gas flow and energy generation for landfills with LFGTE projects. 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 reported the amount recovered based on measurements of gas flow and concentration, and the reporting accounted for changes over time. If both flare data and LMOP recovery data were available for any of the remaining landfills (i.e., not in the EIA database), then the emissions recovery was 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 data, on the other hand, only provided a range of landfill gas flow for a given flare size. 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 for the current Inventory can be found in Annex 3.14.

A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided. The value for efficiency 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, Chapter 2.4 (EPA 2008), efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in LMOP.

Emissions from industrial landfills were estimated from activity data for industrial production (ERG 2011), waste disposal factors, and the first order decay model. As over 99 percent of the organic waste placed in industrial 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). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten 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 landfills.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from 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 landfill for each year of its operation. 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 landfills, are representative of U.S. landfills.

Additionally, the approach used to estimate the contribution of industrial wastes to total CH_4 generation introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation by cover soils. There is also uncertainty in the estimates of CH_4 that is recovered by flaring and energy projects. The IPCC default value of 10 percent for uncertainty in recovery estimates was used in the uncertainty analysis when metering was in place (for about 64 percent of the CH_4 estimated to be recovered). For flaring without metered recovery data (approximately 34 percent of the CH_4 estimated to be recovered), a much higher uncertainty of approximately 50 percent was used (e.g., when recovery was estimated as 50 percent of the flare's design capacity).

N_2O emissions from the application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. N_2O emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills 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, any uncertainty or bias caused by not including N_2O emissions from landfills is expected to be minimal.

The results of the IPCC Good Practice Guidance Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2010 were estimated to be between 51.3 and 154.5 Tg CO_2 Eq., which indicates a range of 52 percent below to 43 percent above the 2010 emission estimate of 107.8 Tg CO_2 Eq.

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	**CH_4**	**107.8**	**51.3**	**154.5**	**-52%**	**+43%**
MSW	CH_4	93.5	39.4	140.6	-58%	+50%
Industrial	CH_4	14.3	10.3	17.3	-28%	+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 2010. 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. 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 made to ensure that emission avoidance from each landfill was calculated in only one of the three databases. 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

No methodological changes were made for this Inventory. The national landfill waste generation data for 2007, 2008, and 2009 were recalculated using the most recent BioCycle data for 2008 (BioCycle 2010). These recalculations resulted in decreased waste generation amounts for those years and, in turn, decreased the total CH_4 emissions estimates from landfills for 2008 and 2009 compared to the previous year's Inventory. The BioCycle survey is the only continually updated nationwide survey of waste generated and disposed in landfills in the United States. For years when BioCycle data are not available, the waste generation data used for the Inventory are extrapolated and later updated as later surveys are published, resulting in changes over the affected portion of the time series.

Planned Improvements

Improvements to the inventory being examined include incorporating data from the EPA's GHGRP and modifying the default oxidation rate applied to MSW and industrial landfills.

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.) will be required to calculate and report their greenhouse gas emissions to EPA through its GHGRP. This consists of the landfill, landfill gas collection systems, and landfill gas destruction devices, including flares. The data collected from the GHGRP will be used in future Inventories to revise the parameters used in the CH_4 generation calculations, including degradable organic carbon (DOC), the flare correction factor, the methane correction factor (MCF), fraction of DOC dissimilated (DOC_F), the destruction efficiency of flares, the oxidation factor, and the decay rate constant (k). The addition of this higher tier data will improve the emission calculations to provide a more accurate representation of greenhouse gas emissions from MSW landfills. . In examining data from EPA's GHGRP that would be useful to improve the emissions estimates for MSW landfills, particular attention will be made to ensure time series consistency, as the facility-level reporting data from the GHGRP are not available for all inventory years as reported in this inventory. In implementing improvements and integration of data from the GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon[229].

In addition to MSW landfills, industrial landfills at facilities generating CH_4 in amounts equivalent to 25,000 metric tons or more of CO_2 Eq. are required to report their GHG emissions in September 2012 through EPA's GHGRP. Similar data for industrial landfills as is required for the MSW landfills will be reported. Any additions or improvements to the Inventory using reported GHGRP data will be made for the industrial landfill portion of the inventory. Improvements may include breaking out the industrial waste landfills into three regions (dry, moderate, and wet) as is done for the MSW landfills, allowing for region-specific k values rather than a default IPCC value. As with MSW landfills, any improvements made to the emissions estimates for industrial landfills will include efforts to ensure time series consistency using the latest guidance from the IPCC.

As a first step toward investigating the possibility of increasing the oxidation rate used in the Inventory, a literature review was conducted in 2011 to assess the state of oxidation at a range of landfills (RTI 2011). A standard CH_4 oxidation rate of 10 percent has been used in the LFG inventory for both industrial and MSW landfills since the inventory began 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 rate of 10 percent may be less than oxidation rates achieved at well-managed landfills with gas collection and control.

Changing the oxidation rate and calculating the amount of CH_4 oxidized from landfills with gas collection and control requires the estimation of waste disposed of in these types of landfills. The Inventory methodology uses waste generation data from the BioCycle State of Garbage reports, which reports the total amount of waste generated and disposed nationwide by state. In 2010, the State of Garbage survey requested data on the recovery of landfill gas for the first time. Twenty-eight states reported that 260 out of 1,414 (18 percent) operational landfills recovered 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.

While the research findings indicate some evidence that landfills with gas collection and control achieve a 20 percent or higher oxidation rate, there is not sufficient certainty to adopt a higher oxidation rate at this time. It is expected that with increased reporting by states in the State of Garbage survey, as well as the data collected through the GHGRP, the oxidation rate for at least a subset of landfills may be increased in a future Inventory.

[Begin Text Box]

Box 8-3: Biogenic Wastes in Landfills

Regarding the depositing of wastes of biogenic origin in landfills, empirical evidence shows that some of these wastes degrade very slowly in landfills, and the C they contain is effectively sequestered in landfills over a period of

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

time (Barlaz 1998, 2006). Estimates of C removals from landfilling of forest products, yard trimmings, and food scraps are further described in the Land Use, Land-Use Change, and Forestry chapter, based on methods presented in IPCC (2003) and IPCC (2006).

[End Box]

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater treatment processes can produce anthropogenic CH_4 and N_2O emissions. Wastewater from domestic[230] 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 2009).

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).

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). 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 nitrogen 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 2010, CH_4 emissions from domestic wastewater treatment were 7.8Tg CO_2 Eq. (370 Gg). Emissions gradually increased 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. In 2010, CH_4 emissions from industrial wastewater treatment were estimated to be 8.6 Tg CO_2 Eq. (409 Gg). Industrial emission sources have 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 8-6 and Table 8-7 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

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[230] Throughout the inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

systems that has been discharged into aquatic environments. The 2010 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (1 Gg) and 4.7 Tg CO_2 Eq. (15.3 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 5.0 Tg CO_2 Eq. (16.3 Gg). 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 8-6: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	2000	2005	2006	2007	2008	2009	2010
CH_4	**15.9**	**17.2**	**16.5**	**16.7**	**16.6**	**16.6**	**16.5**	**16.3**
Domestic	8.8	8.9	8.3	8.2	8.1	8.0	8.0	7.8
Industrial*	7.1	8.4	8.2	8.5	8.5	8.6	8.5	8.6
N_2O	**3.5**	**4.3**	**4.7**	**4.8**	**4.8**	**4.9**	**5.0**	**5.0**
Domestic	3.5	4.3	4.7	4.8	4.8	4.9	5.0	5.0
Total	**19.4**	**21.5**	**21.2**	**21.5**	**21.4**	**21.5**	**21.5**	**21.3**

[*] 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 8-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	2000	2005	2006	2007	2008	2009	2010
CH_4	**758**	**821**	**785**	**794**	**791**	**792**	**787**	**779**
Domestic	421	423	397	391	386	383	380	370
Industrial*	338	398	389	403	405	409	406	409
N_2O	**11**	**14**	**15**	**15**	**16**	**16**	**16**	**16**
Domestic	11	14	15	15	16	16	16	16

* 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 (20 percent), an emission factor (10.7 g CH_4/capita/day) and converting that to Gg/year. Methane emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (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 aerobic (zero or 0.3) and anaerobic (0.8) systems with all aerobic systems assumed to be well-managed. Methane emissions 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:

$$\textit{Emissions from Septic Systems} = \mathrm{A}$$
$$= \mathrm{US_{POP}} \times (\%\ \mathrm{onsite}) \times (\mathrm{EF_{SEPTIC}}) \times 1/10\text{^}9 \times \mathrm{Days}$$

$$\textit{Emissions from Centrally Treated Aerobic Systems} = \mathrm{B}$$

= [(% 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) × 1/10^6

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) × 1/10^6

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 (Gg) = 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 Gg
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 (gal)
digester gas = Cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) (Metcalf and Eddy 1991)
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 Gg

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2011) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. Table 8-8 presents U.S. population and total BOD_5 produced for 1990 through 2010, while Table 8-9 presents domestic wastewater CH_4 emissions for both septic and centralized systems in 2010. 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, and 2009 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2009), with data for intervening years obtained by linear interpolation. 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 2010 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 (1991 and 2003). The CH_4 emission factor (0.6 kg CH_4/kg BOD_5) and the MCF 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, and in recommendations for closed flares used by the Landfill Methane Outreach Program (LMOP). 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 (1991). 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 8-8: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	253	8,333
2000	286	9,414
2005	300	9,864
2006	303	9,958
2007	306	10,057
2008	309	10,149
2009	311	10,236
2010	313	10,278

Source: U.S. Census Bureau (2011); Metcalf & Eddy 1991 and 2003.

Table 8-9: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2010)

	CH_4 emissions (Tg CO_2 Eq.)	**% of Domestic Wastewater CH_4**
Septic Systems	5.1	65.4%
Centralized Systems	2.7	34.6%
Total	**7.8**	**100%**

Note: Totals may not sum due to independent rounding.

Industrial Wastewater CH_4 Emission Estimates

Methane emissions 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. High volumes of wastewater generated and a high organic wastewater load were the main criteria. 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 2010 are displayed in Table 8-10 below. Table 8-11 contains production data for these industries.

Table 8-10: Industrial Wastewater CH_4 Emissions by Sector (2010)

	CH_4 emissions (Tg CO_2 Eq.)	% of Industrial Wastewater CH_4
Pulp & Paper	4.1	48%
Meat & Poultry	3.6	42%
Petroleum Refineries	0.6	7%
Fruit & Vegetables	0.1	1%
Ethanol Refineries	0.1	1%
Total	**8.6**	**100%**

Note: Totals may not sum due to independent rounding.

Table 8-11: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, and Petroleum Refining Production (Tg)

Year	Pulp and Paper	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.7	702.4
2000	142.8	32.1	22.2	50.9	4.9	795.2
2005	131.4	31.4	25.1	42.9	11.7	818.6
2006	137.4	32.5	25.5	42.9	14.5	826.7
2007	135.9	33.4	26.0	44.7	19.4	827.6
2008	134.5	34.4	26.6	45.1	26.9	836.8
2009	137.0	33.8	25.2	46.5	31.7	822.4
2010	137.0	33.7	25.9	43.7	39.5	848.6

Methane 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 percentage of organic loading assumed to degrade anaerobically, and the maximum CH_4 producing potential of industrial wastewater (B_o). 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 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

As described below, the values presented in Table 8-12 were used in the emission calculations and are described in detail in Aguiar and Bartram (2008).

Table 8-12: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (%)

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
$\%TA_s$	10.5	33	25	4.2	33.3	75	100
$\%Plants_o$	60	100	100	11	100	100	100
$\%Plants_a$	25	33	25	5.5	33.3	75	100
$\%Plants_t$	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

Source: Aguiar and Bartram (2008) Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. August 10, 2008.

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. No anaerobic activity is assumed to occur in activated sludge systems or aerated stabilization basins (note: although IPCC recognizes that some CH_4 can be emitted from anaerobic pockets, they recommend an MCF of zero). However, about 25 percent of the wastewater treatment systems used in the United States are non-aerated stabilization basins. These basins are typically 10 to 25 feet deep. These systems are classified as anaerobic deep lagoons (MCF = 0.8).

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). Published data from the American Forest and Paper Association, data published by Paper Loop, and other published statistics were used to estimate production for 2002 through 2010 (Pulp and Paper 2005, 2006, and monthly reports from 2003 through 2008; Paper 360° 2007). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999).

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 2011). 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.

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 2011) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 8-13, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors.

Table 8-13: 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	8.71	0.797
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.78	1.831

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. According to the Renewable Fuels Association, 82 percent of ethanol production facilities use corn as the sole feedstock and 7 percent of facilities use a combination of corn and another starch-based feedstock. The fermentation of corn is the principal ethanol production process in the United States and is expected to increase through 2012, and potentially more; therefore, emissions associated with wastewater treatment at starch-based ethanol production facilities were estimated (ERG 2006).

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 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 (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times \%\ \text{Not Recovered}] + [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times B_o \times \text{MCF} \times (\%\ \text{Recovered}) \times (1\text{-DE})] \text{ x } 1/10\text{\^{}}9$$

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
$\%\text{Plants}_o$ = percent of plants with onsite treatment (100%)
$\%\text{WW}_{a,p}$ = percent of wastewater treated anaerobically in primary treatment (0%)
$\%\text{COD}_p$ = percent of COD entering primary treatment (100%)
$\%\text{Plants}_a$ = percent of plants with anaerobic secondary treatment (33.3% wet, 75% dry)
$\%\text{Plants}_t$ = percent of plants with other secondary treatment (66.7% wet, 25% dry)
$\%\text{WW}_{a,s}$ = percent of wastewater treated anaerobically in anaerobic secondary treatment (100%)
$\%\text{WW}_{a,t}$ = percent of wastewater treated anaerobically in other secondary treatment (0%)
$\%\text{COD}_s$ = 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 Gg

A time series of CH_4 emissions for 1990 through 2010 was developed based on production data from the Renewable Fuels Association (RFA 2011).

Petroleum Refining. Petroleum refining wastewater treatment operations produce CH_4 emissions from anaerobic wastewater treatment. The wastewater inventory section includes CH_4 emissions from petroleum refining wastewater treated on site under intended or unintended anaerobic conditions. Most facilities use aerated biological systems, such as trickling filters or rotating biological contactors; these systems can also exhibit anaerobic conditions that can result in the production of CH_4. Oil/water separators are used as a primary treatment method; however, it is unlikely that any COD is removed in this step.

Available information from the industry was compiled. The wastewater generation rate, from CARB (2007) and Timm (1985), was determined to be 35 gallons per barrel of finished product. 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:

$$\text{Methane} = \text{Flow} \times \text{COD} \times B_o \times \text{MCF}$$

where,

Flow = Annual flow treated through anaerobic treatment system (m^3/year)
COD = COD loading in wastewater entering anaerobic treatment system (kg/m^3)
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 2010 was developed based on production data from the Energy Information Association (EIA 2011).

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 (Gg)
N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (Gg)
$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (Gg)
$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (Gg)
$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (Gg)
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 (EPA 2008)
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 2011) 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, and 2009 American Housing Survey (U.S. Census 2009). Data for intervening years were obtained by linear interpolation. 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 U.S. Department of Agriculture Economic Research Service (USDA 2009). Protein consumption data for 2005 through 2010 were extrapolated from data for 1990 through 2004. Table 8-14 presents the data for U.S. population and average protein intake. 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. 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 2009 were forecasted from the rest of the time series. 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. In 2010, 274 Gg N was removed with sludge.

Table 8-14: U.S. Population (Millions), Available Protein (kg/person-year), and Protein Consumed (kg/person-year)

Year	Population	Available Protein	Protein Consumed
1990	253	38.7	29.6
2000	286	41.3	31.6
2005	300	41.7	32.0
2006	303	41.9	32.2
2007	306	42.1	32.3
2008	309	42.2	32.4
2009	311	42.4	32.5
2010	313	42.6	32.7

Source: U.S. Census Bureau 2011, USDA 2009.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2010 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the IPCC Good Practice Guidance Tier 2 methodology (2000). 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 Tier 2 quantitative uncertainty analysis are summarized in Table 8-15. Methane emissions from wastewater treatment were estimated to be between 12.3 and 21.5 Tg 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 25 percent below to 31 percent above the 2010 emissions estimate of 16.3 Tg CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be between 1.2 and 10.1 Tg CO_2 Eq., which indicates a range of approximately 77 percent below to 99 percent above the 2010 emissions estimate of 5.0 Tg CO_2 Eq.

Table 8-15: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2010 Emission Estimate (Tg CO2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Wastewater Treatment	**CH_4**	**16.3**	**12.3**	**21.5**	**-25%**	**+31%**
Domestic	CH_4	7.8	5.8	9.9	-26%	+28%
Industrial	CH_4	8.6	5.1	13.3	-41%	+54%
Wastewater Treatment	**N_2O**	**5.0**	**1.2**	**10.1**	**-77%**	**+99%**

[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 2010. 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

For domestic wastewater CH_4 calculations, the emission estimations were updated for septic systems using new research from WERF (Leverenz et al. 2010). Previously, the septic equation used MCF and BOD produced (Gg/yr) along with percent of wastewater treated and B_o to estimate emissions. In the current Inventory, that calculation was updated with a new emission factor of 10.7 g CH_4/capita/day, which uses population along with percent of wastewater treated and B_o for estimating emissions. This recalculation caused changes from the 1990 through 2009 Inventory for all years. Other minor updates in input data such as population and production resulted in slight changes in the later years of the Inventory.

For domestic wastewater N_2O calculations, an update was made to the $N_2O_{EFFLUENT}$ equation to make it more accurately reflect emissions. U.S. population is now multiplied by the fraction of the population not using septic systems for wastewater treatment. In addition, the factor for industrial and commercial co-discharged protein was previously left out of the calculations. This error was fixed in the current Inventory. These updates caused changes from the 1990 through 2010 Inventory for all years. Other minor updates in input data such as population resulted in slight changes in the later years of the Inventory.

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. Recently available 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.

For industrial wastewater emissions, data recently collected by EPA's Office of Air for pulp and paper mills and petroleum refineries will be evaluated to determine if sufficient information is available to update the estimates of wastewater generated per unit of production and the percent of industry wastewater treated anaerobically in these industries (%TA). Initial evaluations of EPA's Office of Air data for pulp and paper manufacturing indicate there is sufficient information to update emission estimates in the next inventory year. Data collected under the EPA's GHGRP will also be investigated for updating this variable. Data collection from industrial wastewater treatment is expected to occur in 2012. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the industrial wastewater 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[231].

Currently, 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.

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. 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. 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.

For the current Inventory, the use of new measurement data from WERF to develop U.S.-specific emission factors for N_2O and CH_4 emissions from septic systems was investigated. The data available to develop an emission factor for CH_4 was determined to be of sufficient quality and was 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 in the current Inventory. 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

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

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.

The value used for N content of sludge continues to be investigated. This value is driving the N_2O emissions for wastewater and is static over the time series. To date, new data has not been identified that would be able to establish a time series for this value.

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. treatment operations for these industries. Previously, both the organic chemicals and the seafood processing industry were investigated to estimate their potential to generate CH_4. Despite the lack of current data, emissions were estimated for both sectors. The organic chemicals industry was estimated to emit 15 Gg/year of CH_4, and seafood processing was estimated to emit 3.0-3.5 Gg/year. Due to the insignificant amount of CH_4 estimated to be emitted and the lack of reliable, up-to-date data, these industries were not selected for inclusion in the industry. Other industries will be reviewed as necessary for inclusion in future years of the Inventory using EPA's Permit Compliance System and Toxics Release inventory. In addition, information from EPA's GHGRP will be used to determine likely candidates for inclusion. As such, sugar processing (beet and cane sugar), beverage (wineries, distilleries, breweries, soft drinks), and dairy (including cheese making) industries have been identified for possible consideration in the future.

8.3. Composting (IPCC Source Category 6D)

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 material, stabilization of the waste, and destruction of pathogens in the waste material. 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, but it is oxidized to a large extent in the aerobic sections of the compost. Anaerobic sections are created in composting piles when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. 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 the N content of the feedstock and how well the compost pile is managed, nitrous oxide (N_2O) emissions can be produced. The sources of N_2O formation are complicated, but are mainly associated with anaerobic conditions, ranging 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 2010, the amount of material composted in the United States has increased from 3,810 Gg to 18,763 Gg, an increase of approximately 392 percent. From 2000 to 2010, the amount of material composted in the United States has increased by approximately 26 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage (see Table 8-16 and Table 8-17). In 2010, CH_4 emissions from composting were 1.6 Tg CO_2 Eq. (75 Gg), and N_2O emissions from composting were 1.7 Tg CO_2 Eq. (5.6 Gg). The wastes that are composted include primarily 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 composting 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. In 1992, 11 states and the District of Columbia had legislation in effect that banned or discouraged disposal of yard trimmings in landfills. Currently, 23 states and the District of Columbia, representing about 50 percent of the nation's population, have enacted such legislation (EPA 2010). The total amount of waste composted has decreased slightly since 2008, by approximately 6 percent.

Table 8-16: CH_4 and N_2O Emissions from Composting (Tg CO_2 Eq.)

Activity	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CH_4	0.3	1.6	1.6	1.7	1.7	1.6	1.6
N_2O	0.4	1.7	1.8	1.8	1.9	1.8	1.7
Total	**0.7**	**3.3**	**3.3**	**3.5**	**3.5**	**3.3**	**3.3**

Table 8-17: CH_4 and N_2O Emissions from Composting (Gg)

Activity	**1990**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
CH_4	15	75	75	79	80	75	75
N_2O	1.1	5.6	5.7	5.9	6.0	5.7	5.6

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 8-16 and Table 8-17 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, Gg CH_4 or N_2O,
M = mass of organic waste composted in Gg,
EF_i = emission factor for composting, 4 g CH_4/kg of waste treated (wet basis) and 0.3 g N_2O/kg of waste treated (wet basis), and
i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 8-18. Estimates of the quantity composted for 1990 and 1995 were taken from the *Characterization of Municipal Solid Waste in the United States: 1996 Update* (Franklin Associates 1997); estimates of the quantity composted for 2000, 2005, 2006, 2007, 2008, and 2009 were taken from EPA's *Municipal Solid Waste In The United States: 2009 Facts and Figures* (EPA 2010); estimates of the quantity composted for 2010 were calculated using the 2009 quantity composted and a ratio of the U.S. population in 2009 and 2010 (U.S. Census Bureau 2011).

Table 8-18: U.S. Waste Composted (Gg)

Activity	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Waste Composted	3,810	14,923	18,643	18,852	19,695	20,049	18,870	18,763

Source: Franklin Associates 1997 and EPA 2009.

Uncertainty and Time-Series Consistency

The estimated uncertainty from the 2006 IPCC Guidelines is ±50 percent for the Tier 1 methodology. Emissions from composting in 2010 were estimated to be between 1.7 and 5.0 Tg CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2010 emission estimate of 3.3 Tg CO_2 Eq. (see Table 8-19).

Table 8-19 : Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (Tg CO_2 Eq. and Percent)

Source	Gas	2010 Emission Estimate (Tg CO2 Eq.)	Uncertainty Range Relative to Emission Estimate			
			(Tg CO2 Eq.)		(%)	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Composting	CH_4, N_2O	3.3	1.66	4.98	-50%	+50%

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2010. Details on the emission trends through time are described in more detail in the Methodology section, above.

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.

In examining data from EPA's GHGRP that would be useful to improve the emission estimates for Composting source 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 (see: <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf>).

8.4. Waste Sources of Indirect Greenhouse Gases – TO BE UPDATED

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 2009 are provided in Table 8-20.

Table 8-20: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	2000	2005	2006	2007	2008	2009
NO_x	**+**	**2**	**2**	**2**	**2**	**2**	**2**
Landfills	+	2	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	+	+	+	+	+	0
CO	**1**	**8**	**7**	**7**	**7**	**7**	**7**
Landfills	1	7	6	6	6	6	6
Wastewater Treatment	+	1	+	+	+	+	+
Miscellaneous[a]	+	+	+	+	+	+	+
NMVOCs	**673**	**119**	**114**	**113**	**111**	**109**	**76**
Wastewater Treatment	57	51	49	49	48	47	33
Miscellaneous[a]	557	46	43	43	42	41	29
Landfills	58	22	22	21	21	21	14

[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 Gg.

Methodology

These emission estimates were obtained from preliminary data (EPA 2010, EPA 2009), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant

Emission Trends web site. 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

were collected for individual source categories from various agencies. Depending on the source 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 2009.

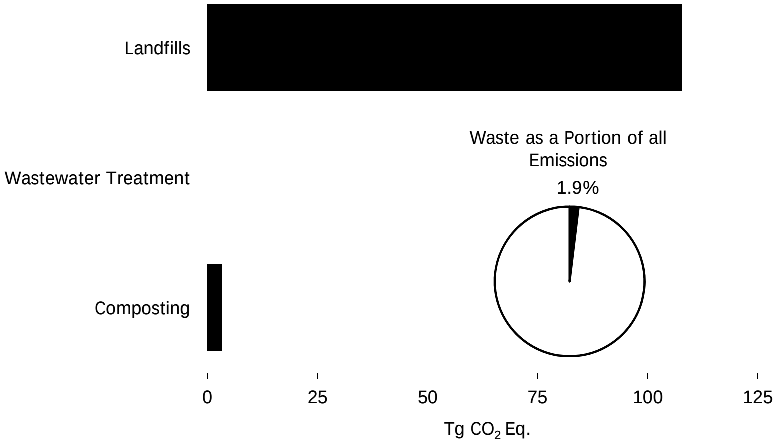

Figure 8-1: 2010 Waste Chapter Greenhouse Gas Sources

9. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

10. 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 are presented in this section; detailed descriptions of each recalculation are contained within each source's description found in this report, if applicable. Table 10-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and sinks and Table 10-2 summarizes the quantitative effect on annual net CO_2 fluxes, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2009 report). These tables present the magnitude of these changes in units of teragrams of carbon dioxide equivalent (Tg CO_2 Eq.).

The Recalculations Discussion section of each source presents the details of each recalculation. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 2009) 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.

The following emission sources and sinks, which are listed in descending order of absolute average annual change in emissions or sequestration between 1990 and 2009, underwent some of the most important methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken is provided for each source.

- *Forest Land Remaining Forest Land (CH_4 & N_2O emissions, CO_2 sink).* Five notable changes in this year's forest carbon inventory methodology affected the national stock and change estimates for forest ecosystems. For the first two changes, inventories adopted the method of Woodall et al. (2011a) for both live and standing dead trees. This affected these two pools in somewhat different ways. Live tree carbon stocks are lower because the new method estimates lower biomass for most trees, but the relative effect on net annual stock change was minimal and varied from state to state. Standing dead tree estimates were changed to Woodall tree-based estimates (Woodall et al. 2011a, Domke et al. 2011, Woodall et al. In Press) and resulted in lower estimates of stocks, yet the newer stock-change estimates included greater sequestration throughout the 21-year interval. The remaining three changes to the inventory originate as modifications in the forest inventory data, specifically the FIADB. A number of Sothern states revised some previously existing inventories from the late 1990s and early 2000s. From this, stock and stock-change estimates varied slightly for seven states over the mid-part of the 1990–2010 interval. In some cases carbon stocks increased while in other inventories they decreased. The net effect is a slight increase in sequestration as estimated for the late 1990s and early 2000s. The fourth change is the addition of the periodic data for Alaska timberlands so that a stock-change estimate is now included for a large part of coastal Alaska. The net effect on the national totals is a slight increase in sequestration applied throughout the interval. Finally, forest area, and thus C stock, estimates were revised upward for central and western portions of Oklahoma and Texas since last year's inventory. These changes resulted in a decrease in CH_4 and N_2O emissions from forest land remaining forest land across the entire time series, with an average annual decrease of 1.8 Tg CO_2 Eq. (20.1 percent) for CH_4 and 1.4 Tg CO_2 Eq. (19.2 percent) for N_2O. These changes also resulted in an increase in C sequestration across the time series, with an average annual increase of 44.9 Tg CO_2 Eq. (8.1 percent).
- *Land Converted to Cropland (CO_2)* Methodological recalculations in this year's inventory were associated with the following improvements: 1) use of the DAYCENT biogeochemical model to estimate soil organic C stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; 4) extension of the tillage activity dataset with statistics from Conservation Technology and Information Center (CTIC 2004); and 5) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). These changes resulted in an

increase in emissions from land converted to cropland across the entire time series, with an average annual increase of 23.4 Tg CO_2 Eq. (819.2 percent).

- *Agricultural Soil Management (N_2O).* Methodological recalculations in this year's inventory were associated with the following improvements: 1) incorporation of MODIS Enhanced Vegetation Index as to reduce uncertainties in the estimation of crop production and subsequent carbon input to the soil; 2) using the National Resources Inventory (NRI) as the basis for crop histories and land use change (USDA-NRCS 2009); 3) addition of specific tillage practices with statistics from Conservation Technology and Information Center (CTIC 2004); 4) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2010 (USDA-ERS 2011); and 5) N2O emissions from rice cultivation were estimated with the recommended emission factor from the IPCC (2006). These changes combined to create an average annual increase of 16.7 Tg CO_2 Eq. (8.0 percent) from agricultural soil management from 1990 through 2009.
- *Wastewater Treatment (CH_4).* For domestic wastewater CH_4 calculations, the emission estimations were updated for septic systems using new research from WERF (Leverenz et al. 2010). Previously, the septic equation used MCF and BOD produced (Gg/yr) along with percent of wastewater treated and B_o to estimate emissions. In the most recent Inventory, that calculation was updated with a new emission factor of 10.7 g CH4/capita/day, which uses population along with percent of wastewater treated and B_o for estimating emissions. This recalculation caused changes from the 1990-2009 Inventory for all years. Other minor updates in input data such as population and production resulted in slight changes in the later years of the Inventory. For domestic wastewater N_2O calculations, an update was made to the $N_2O_{EFFLUENT}$ equation to make it more accurately reflect emissions. U.S. population is now multiplied by the fraction of the population not using septic systems for wastewater treatment. In addition, the factor for industrial and commercial co-discharged protein was previously left out of the calculations. This error was fixed in the 1990-2010 Inventory. These updates caused changes from the 1990-2009 Inventory for all years. Other minor updates in input data such as population resulted in slight changes in the later years of the Inventory. These changes resulted in an average annual decrease of 7.9 Tg CO_2 Eq. (32.0 percent) in CO_2 emissions from wastewater treatment for the period 1990 through 2009.
- *Cropland Remaining Cropland (CO_2), Grassland Remaining Grassland (CO_2)*, and *Land Converted to Grassland (CO_2).* Methodological recalculations in this year's inventory were associated with the following improvements: 1) use of the DAYCENT biogeochemical model to estimate soil organic C stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; and 4) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). These changes resulted in an increase in C sequestration from cropland remaining cropland and grassland remaining grassland across the entire time series, with an average annual increase of 4.3 Tg CO_2 Eq. (24.6 percent) and 5.3 Tg CO_2 Eq. (198.3 percent), respectively. These changes also resulted in a decrease in C sequestration from land converted to grassland across the entire time series, with an average annual decrease of 13.5 Tg CO_2 Eq. (59.2 percent).
- *Fossil Fuel Combustion (CO_2).* For the current Inventory, the Energy Information Administration updated energy consumption statistics across the time series. These revisions primarily impacted the emission estimates at the end-use sector level for 2008 and 2009; however, revisions to industrial petroleum consumption impacted estimates across the time series. Another one of the revisions that were made this year was incorporating motor vehicle age distribution from EPA's MOtor Vehicle Emission Simulator (MOVES) model. MOVES is EPA's tool for estimating emissions from highway vehicles, based on analysis of millions of emission test results and considerable advances in EPA's understanding of vehicle emissions. Population data from the MOVES model was used to estimate the age distribution of motor vehicles in the United States. Overall, these changes resulted in an average annual increase of 5.1 Tg CO_2 Eq. (0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2009.
- *Non-Energy Uses of Fossil Fuels (CO_2).* Relative to the previous Inventory, emissions from non-energy uses of fossil fuels decreased by an average of 3.6 Tg CO_2 Eq. (2.6 percent) across the entire time series. This decline is not attributable to a change in NEU methodology. It was caused by a change in petrochemical input data reported by the Energy Information Administration in its Monthly Energy Review. In particular, a decline in EIA's estimate of petroleum coke consumed for non-energy purposes across the time series explains the vast majority of the decrease.

- *Enteric Fermentation (CH_4).* There were several modifications to the estimates relative to the previous Inventory that had an effect on emission estimates, including the following:

  The previous Inventory report estimated emissions from bulls using Tier 1 methods, while the rest of the cattle population was estimated using Tier 2. The current Inventory now applies Tier 2 methods to estimate emissions from bulls for each year. Revisions to the DE values for foraging cattle diets were applied to all years covered by this inventory, resulting in an average change of less than 0.1 percent for foraging beef cattle emissions estimates for 1990 through 2006 and an average increase of 0.4 percent for 2007 through 2009. During the QA/QC process, it was realized that the one data point from 1988 (total births) had been revised by USDA since its original download. Therefore, the data point was corrected from 39,318.0 to 39,317.9 thousand births. This is a very minor change, but it is noted in detail specifically because it affects 1990 base year emissions by trickling through the transition matrix in the growing populations for 1989 and 1990.

  The equations used to distribute end-of-year remaining populations for feedlot cattle to the individual state populations were updated so that the population proportions reflect the current year rather than the following year populations. Emission estimates are also now included for American bison and mules, burros, and donkeys for all years, and contribute an average of 0.2 percent of total emissions from enteric fermentation across the time series.

  The USDA published revised estimates in several categories that affected historical emissions estimated for cattle, including slight revisions in 2009 cattle on feed population estimates for "other states" (aggregated data for states with small populations of cattle on feed), dairy cow milk production for several states, and steer and heifer placement and slaughter statistics. Additionally, calf births were revised for both the 2008 and 2009 estimates. These changes had an insignificant impact on the overall results.

  There were also additional population changes for goats from 2003 through 2006, sheep for 2004, 2006, and 2009, and swine in 2009, as discussed in the recalculations discussion for manure management. As a result of these changes, overall methane emissions from enteric fermentation increased an average of 2.3 Tg CO_2 Eq. (1.7 percent) per year for 1990 through 2009.

  These changes resulted in an increase in emissions from enteric fermentation across the entire time series, with an average annual increase of 2.3 Tg CO_2 Eq. (1.7 percent).

- *Stationary Combustion (CH_4 and N_2O).* Historical N_2O emissions from stationary sources were revised due to a few changes that impacted the entire time series. Slight changes to emission estimates for sectors are due to revised data from EIA. Wood consumption data in EIA were revised for the residential, commercial, electric power, and industrial sectors from 1990 to 2009. Additionally, a Tier 2 emission estimation methodology was applied to estimate emissions from the electric power sector across the entire time series. This primarily impacted N_2O emission estimates as the number of coal fluidized bed boilers increased significantly from 2000 through 2005. The combination of the methodological and historical data changes resulted in an average annual increase of 2.0 Tg CO_2 Eq. (13.8 percent) in N_2O emissions from stationary combustion for the period 1990 through 2009.

- *Electrical Transmission and Distribution (SF_6).* SF_6 emission estimates for the period 1990 through 2009 were updated based on 1) new data from EPA's SF_6 Emission Reduction Partnership; 2) revisions to interpolated and extrapolated non-reported Partner data; and 3) a correction made to 1999-2001 reported emissions data for a Partner. Correcting the reported emissions not only directly impacted overall emissions for 1999-2001, but also impacted the regression coefficient used to estimate emissions for non-Partners, which is based on the relationship between transmission miles and emissions for Partners that reported emissions in 1999. Specifically, the regression coefficient for utilities with fewer than 10,000 transmission miles decreased from 1.001 kg of emissions per transmission mile to 0.89 kg of emissions per transmission mile. Based on the revisions listed above, SF_6 emissions from electrical transmission and distribution decreased between 6 and 9 percent for each year from 1990 through 2009, with an average decrease of 1.3 Tg CO_2 Eq. (6.8 percent).

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990	2000	2005	2006	2007	2008	2009
CO_2	**0.7**	**(0.2)**	**0.5**	**5.1**	**7.5**	**7.2**	**(1.8)**
Fossil Fuel Combustion	3.7	2.5	4.2	13.5	14.4	13.6	5.7
Electricity Generation	NC	+	NC	NC	NC	+	(7.6)
Transportation	NC	NC	NC	NC	NC	(0.1)	0.5
Industrial	3.7	2.5	4.2	13.5	14.4	11.7	12.6
Residential	NC	+	NC	NC	NC	1.1	(0.1)
Commercial	NC	+	NC	NC	NC	0.9	0.4
U.S. Territories	NC	NC	NC	NC	NC	NC	+
Non-Energy Use of Fuels	(2.8)	(2.5)	(3.8)	(7.6)	(6.8)	(5.9)	(5.1)
Iron and Steel Production & Metallurgical Coke Production	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Natural Gas Systems	+	+	0.2	(0.6)	+	+	+
Cement Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	+	+	(0.5)
Urea Consumption for Non-Ag Purposes	NC	NC	NC	NC	+	+	(0.5)
Lime Production	NC	NC	NC	NC	NC	NC	+
Incineration of Waste	NC	+	+	+	+	(0.3)	(0.6)
Limestone and Dolomite Use	NC	NC	NC	NC	NC	NC	NC
Cropland Remaining Cropland	NC	NC	NC	NC	+	+	(0.7)
Soda Ash Production and Consumption	NC	NC	NC	NC	NC	+	(0.7)
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	+	+	+	+	+	+	+
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC	0.1
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Zinc Production	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	+
Wetlands Remaining Wetlands	NC	NC	NC	NC	NC	NC	+
Phosphoric Acid Production	NC	NC	NC	NC	NC	+	+
Lead Production	NC	NC	NC	NC	NC	NC	NC
Petroleum Systems	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.1)
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Land Use, Land-Use Change, and Forestry (Sink)[a]	*51.9*	*(82.7)*	*(12.4)*	*(53.9)*	*(15.3)*	*(15.0)*	*(15.6)*
Biomass - Wood[b]	*(0.8)*	*(0.9)*	*(1.2)*	*(1.2)*	*(1.1)*	*(1.0)*	*(2.0)*
International Bunker Fuels[b]	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*	*NC*
Biomass - Ethanol[b]	+	+	+	+	+	+	*1.0*
CH_4	**(6.6)**	**(9.4)**	**2.3**	**(25.7)**	**(8.1)**	**(13.6)**	**(14.5)**
Natural Gas Systems	(0.2)	(0.2)	8.0	(18.2)	0.3	(3.8)	(0.8)
Enteric Fermentation	1.7	2.3	2.5	2.5	2.8	2.8	2.8
Landfills	0.3	(0.6)	0.2	+	0.5	(2.8)	(6.3)
Coal Mining	NC	NC	(0.1)	(0.1)	+	(0.2)	(0.9)
Manure Management	+	+	1.3	1.6	1.9	2.3	1.3
Petroleum Systems	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.3)
Wastewater Treatment	(7.6)	(7.9)	(7.8)	(7.8)	(7.8)	(7.9)	(8.0)
Rice Cultivation	NC	NC	NC	NC	NC	NC	NC
Forest Land Remaining Forest Land	(0.7)	(2.8)	(1.7)	(3.6)	(5.5)	(3.1)	(2.0)
Stationary Combustion	+	+	0.1	0.1	0.1	0.1	0.1
Abandoned Underground Coal Mines	NC	NC	NC	NC	(0.3)	(0.6)	(0.4)
Mobile Combustion	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	NC	(0.1)
Petrochemical Production	NC	NC	NC	NC	NC	+	+
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	NC	NC

Field Burning of Agricultural Residues	(0.1)	+	+	+	+	+	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[b]	*NC*	+	+	+	+	+	+
N_2O	**12.5**	**16.3**	**23.3**	**25.6**	**27.1**	**23.8**	**27.0**
Agricultural Soil Management	13.9	18.9	16.3	17.7	17.9	18.9	20.0
Mobile Combustion	NC	NC	NC	NC	NC	NC	NC
Stationary Combustion	(0.6)	(0.2)	5.9	6.4	6.7	7.0	8.0
Manure Management	0.3	0.3	0.3	0.4	0.4	0.3	0.3
Nitric Acid Production	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Forest Land Remaining Forest Land	(0.6)	(2.2)	(1.4)	(3.0)	(4.5)	(2.6)	(1.7)
Wastewater Treatment	(0.2)	(0.2)	(0.1)	(0.1)	+	+	(0.1)
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Adipic Acid Production	NC	NC	2.5	4.6	7.0	0.5	0.9
Composting	NC	NC	NC	NC	NC	NC	(0.1)
Settlements Remaining Settlements	NC	NC	NC	NC	+	+	(0.1)
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wetlands Remaining Wetlands	NC	NC	NC	NC	NC	NC	+
International Bunker Fuels[b]	*(0.9)*	*(0.8)*	*(0.9)*	*(1.0)*	*(1.0)*	*(1.1)*	*(1.0)*
HFCs	**NC**	**NC**	**+**	**+**	**+**	**+**	**+**
Substitution of Ozone Depleting Substances	NC	NC	+	+	+	+	+
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
PFCs	**(0.1)**	**+**	**NC**	**NC**	**NC**	**NC**	**NC**
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Aluminum Production	(0.1)	+	NC	NC	NC	NC	NC
SF_6	**(1.7)**	**(1.0)**	**(1.2)**	**(1.1)**	**(1.1)**	**(1.2)**	**(1.0)**
Electrical Transmission and Distribution	(1.7)	(1.0)	(1.2)	(1.1)	(1.1)	(1.2)	(1.0)
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	NC	NC	NC	NC	NC	NC
Net Change in Total Emissions[b]	**4.8**	**5.8**	**24.8**	**3.9**	**25.4**	**16.2**	**9.8**
Percent Change	**0.1%**	**0.1%**	**0.3%**	**0.1%**	**0.3%**	**0.2%**	**0.1%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
Parentheses indicate negative values
NC (No Change)
[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.
Note: Totals may not sum due to independent rounding.

Table 10-2: Revisions to Annual Net CO_2 Fluxes from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Component: Net CO_2 Flux From Land Use, Land-Use Change, and Forestry	**1990**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**
Forest Land Remaining Forest Land	(20.3)	(103.1)	(29.4)	(46.1)	(47.3)	(47.3)	(47.5)
Cropland Remaining Cropland	(6.0)	(5.9)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Land Converted to Cropland	32.2	25.7	14.1	14.3	14.0	14.0	14.0
Grassland Remaining Grassland	32.5	(13.7)	(9.1)	(33.4)	5.7	5.7	5.7
Land Converted to Grassland	13.5	14.2	12.7	12.0	13.1	13.0	12.8
Settlements Remaining Settlements	NC	NC	NC	NC	NC	NC	NC
Other	NC	NC	(0.1)	+	+	0.3	+
Net Change in Total Flux	51.9	(82.7)	(12.4)	(53.9)	(15.3)	(15.0)	(15.6)
Percent Change	**6.0%**	**-14.3%**	**-1.2%**	**-5.1%**	**-1.4%**	**-1.4%**	**-1.5%**

NC (No Change)

Note: Numbers in parentheses indicate a decrease in estimated net flux of CO_2 to the atmosphere, or an increase in net sequestration.

Note: Totals may not sum due to independent rounding.

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent

11. References

Executive Summary

BEA (2010) *2009 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2009*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, DC. July 29, 2010. Available online at < http://www.bea.gov/national/index.htm#gdp >.

EIA (2010) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, September 2010,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2009/09).

EIA (2009) International Energy Annual 2007. Energy Information Administration (EIA), U.S. Department of Energy. Washington, DC. Updated October 2008. Available online at <http://www.eia.doe.gov/emeu/iea/carbon.html >.

EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

EPA (2009). "1970 - 2008 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon , D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) Good Practice Guidance for Land Use, Land-Use Change, and Forestry. National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, J. Penman, et al. (eds.). Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>. August 13, 2004.

IPCC (2001) Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

IPCC (2000) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. , National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. Montreal. May 2000. IPCC-XVI/Doc. 10 (1.IV.2000).

IPCC (1996) Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. (eds.). Cambridge University Press. Cambridge, United Kingdom.

IPCC/UNEP/OECD/IEA (1997) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

UNFCCC (2003) National Communications: Greenhouse Gas Inventories from Parties included in Annex I to the Convention, UNFCCC Guidelines on Reporting and Review. Conference of the Parties, Eighth Session, New Delhi. (FCCC/CP/2002/8). March 28, 2003.

U.S. Census Bureau (2010) U.S. Census Bureau International Database (IDB). Available online at <http://www.census.gov/ipc/www/idbnew.html>. August 15, 2010.

Introduction

CDIAC (2009) "Recent Greenhouse Gas Concentrations." T.J. Blasing; DOI: 10.3334/CDIAC/atg.032. Available online at <http://cdiac.ornl.gov/pns/current_ghg.html>. 23 February 2010.

EPA (2009) Technical Support Document for the Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act. U.S. Environmental Protection Agency. December 2009.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon , D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) Good Practice Guidance for Land Use, Land-Use Change, and Forestry. National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, J. Penman, et al. (eds.). Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>. August 13, 2004.

IPCC (2001) Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

IPCC (2000) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. , National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. Montreal. May 2000. IPCC-XVI/Doc. 10 (1.IV.2000).

IPCC (1999) Aviation and the Global Atmosphere. Intergovernmental Panel on Climate Change, , J.E. Penner, et al. (eds.). Cambridge University Press. Cambridge, United Kingdom.

IPCC (1996) Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. (eds.). Cambridge University Press. Cambridge, United Kingdom.

IPCC/TEAP (2005) *Special Report: Safeguarding the Ozone Layer and the Global Climate System, Chapter 4: Refrigeration*. 2005. Available at http://www.auto-ts.com/hcfc/technology%20option/Refrigeration/transport%20refrigeration.pdf

IPCC/UNEP/OECD/IEA (1997) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Jacobson, M.Z. (2001) “Strong Radiative Heating Due to the Mixing State of Black Carbon in Atmospheric Aerosols.” Nature, 409:695-697.

NOAA/ESRL (2009) “Trends in Atmospheric Carbon Dioxide.” Available online at <http://www.esrl.noaa.gov/gmd/ccgg/trends/>. 11 January 2010.

UNEP/WMO (1999) Information Unit on Climate Change. Framework Convention on Climate Change. Available online at <http://unfccc.int>.

UNFCCC (2006) Updated UNFCCC reporting guidelines on annual inventories following incorporation of the provisions of decision 14/CP.11. Note by the secretariat. (FCCC/SBSTA/2006/9). United Nations Office at Geneva, Geneva.

UNFCCC (2006) Updated UNFCCC Reporting Guidelines on Annual Inventories Following Incorporation of the Provisions of Decision 14/CP.11. United Nations Framework Convention on Climate Change, Nairobi. (FCCC/SBSTA/2006/9). August 16, 2006.

Trends in Greenhouse Gas Emissions

BEA (2010) *2009 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2009*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, DC. July 29, 2010. Available online at < http://www.bea.gov/national/index.htm#gdp >.

Duffield, J. (2006) Personal communication. Jim Duffield, Office of Energy Policy and New Uses, USDA and Lauren Flinn, ICF International. December 2006.

EIA (2011) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, January 2011,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2011/01).

EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

EPA (2009). "1970 - 2008 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>

IPCC (2001) Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

U.S. Census Bureau (2010) U.S. Census Bureau International Database (IDB). Available online at <http://www.census.gov/ipc/www/idbnew.html>. August 15, 2010.

Energy

EIA (2010) Indicators: CO_2 Emissions. *International Energy Statistics 2010*. Energy Information Administration <http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm>.

Carbon Dioxide Emissions from Fossil Fuel Combustion

AAR (2009 through 2010) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, DC.

AISI (2004 through 2011) *Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

APTA (2007 through 2010) *Public Transportation Fact Book.* American Public Transportation Association, Washington, DC. Available online at <http://www.apta.com/resources/statistics/Pages/transitstats.aspx>.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, DC. Available online at <http://www.apta.com/research/stats/rail/crsum.cfm>.

BEA (2011) *2010 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2010*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, DC. July 29, 2011. Available online at < http://www.bea.gov/national/index.htm#gdp >.

BEA (1991 through 2009) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, DC.

Benson, D. (2002 through 2004) Unpublished data. Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

Coffeyville Resources Nitrogen Fertilizers (2011). Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Dakota Gasification Company (2006) *CO_2 Pipeline Route and Designation Information*. Bismarck, ND. Available online at <http://www.dakotagas.com/SafetyHealth/Pipeline_Information.html>.

DESC (2011) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, DC.

DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.

DOC (1991 through 2011) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, DC.

DOE (1993 through 2010) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-5198.

DOT (1991 through 2010) *Fuel Cost and Consumption*. Federal Aviation Administration, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC. DAI-10.

EIA (2011a) *Annual Energy Review 2010*. Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0384(2011). October 19, 2011.

EIA (2011b) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, September 2011,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2011/09).

EIA (2011c) *Quarterly Coal Report: January-March 2011*.Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0121.

EIA (2011d) U.S. Energy-Related Carbon Dioxide Emissions, 2010. Energy Information Administration, U.S. Department of Energy. Washington, DC. August 2011. Available online at <http://www.eia.gov/environment/emissions/carbon/>.

EIA (2009a) *Emissions of Greenhouse Gases in the United States 2008, Draft Report.* Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE-EIA-0573(2009).

EIA (2009b) *Natural Gas Annual 2008.* Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0131(06). November 2009.

EIA (2009c) *Manufacturing Consumption of Energy 2006*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Released July, 2009.

EIA (2007a) Personal Communication. Joel Lou, Energy Information Administration. and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2007b) *Historical Natural Gas Annual, 1930 – 2007*. Energy Information Administration, U.S. Department of Energy. Washington, DC.

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at <http://www.eia.doe.gov/fuelalternate.html>.

EIA (2001) *U.S. Coal, Domestic and International Issues*. Energy Information Administration, U.S. Department of Energy. Washington, DC. March 2001.

EIA (1991 through 2009) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0535-annual.

EPA (2011). Acid Rain Program Dataset 1996-2010. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2010a). Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2010b*) NONROAD 2009a Model*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/oms/nonrdmdl.htm>.

Erickson, T. (2003) *Plains CO_2 Reduction (PCOR) Partnership*. Presented at the Regional Carbon Sequestration Partnership Meeting Pittsburgh, Pennsylvania, Energy and Environmental Research Center, University of North Dakota. November 3, 2003. Available online at <http://www.netl.doe.gov/publications/proceedings/03/carbon-seq/Erickson.pdf>.

FAA (2011) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). January 2010.

FAA (2008). *FAA Aerospace Forecasts Fiscal Years 2008–2025*. Table 30 "General Aviation Aircraft Fuel Consumption," Federal Aviation Administration. Available online at < http://www.faa.gov/data_statistics/aviation/aerospace_forecasts/2007-2020/media/FORECAST%20BOOK%20SM.pdf/>.

FAA (2006). *System for assessing Aviation's Global Emission (SAGE) Model*. Federal Aviation Administration's

Office of Aviation Policy, Planning, and Transportation Topics, 2006.

Fitzpatrick, E. (2002) *The Weyburn Project: A Model for International Collaboration*. Available online at <http://www.netl.doe.gov/coalpower/sequestration/pubs/mediarelease/mr-101102.pdf>.

FHWA (1996 through 2010) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, DC. Report FHWA-PL-96-023-annual. Available online at <http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm>.

FRB (2011) *Industrial Production and Capacity Utilization*. Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at <http://www.federalreserve.gov/releases/G17/table1_2.htm> November 16, 2010.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Jacobs, G. (2010) Personal communication. Gwendolyn Jacobs, Energy Information Administration and Rubaab Bhangu, ICF International. *U.S. Territories Fossil Fuel Consumption, 1990–2009.* Unpublished. U.S. Energy Information Administration. Washington, DC.

Marland, G. and A. Pippin (1990) “United States Emissions of Carbon Dioxide to the Earth’s Atmosphere by Economic Activity.” *Energy Systems and Policy,* 14(4):323.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration , U.S. Department of Energy. Washington, DC. June 22, 2001.

USAF (1998) *Fuel Logistics Planning.* U.S. Air Force: AFPAM23-221. May 1, 1998.

U.S. Bureau of the Census (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

USGS (1991 through 2011) *Minerals Yearbook: Manufactured Abrasives Annual Report.* U.S. Geological Survey, Reston, VA.

USGS (1994 through 2011) *Minerals Yearbook: Lead Annual Report.* U.S. Geological Survey, Reston, VA.

USGS (1995, 1998, 2000 through 2002, 2007, and 2009) *Mineral Yearbook: Aluminum Annual Report.* U.S. Geological Survey, Reston, VA.

USGS (1991 through 2010a) *Minerals Yearbook: Silicon Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2010b) *Mineral Yearbook: Titanium Annual Report.* U.S. Geological Survey, Reston, VA.

Stationary Combustion (excluding CO_2)

EIA (2011a) *Annual Energy Review 2010*. Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0384(2011). October 19, 2011.

EIA (2011b) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, September 2011,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2011/09).

EPA (2011). Acid Rain Program Dataset 1996-2010. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2010a*) NONROAD 2009a Model*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/oms/nonrdmdl.htm>.

EPA (2010b). “2009 Average annual emissions, all criteria pollutants in MS Excel.” National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards.

EPA (2003) E-mail correspondance. Air pollutant data. Office of Air Pollution to the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. , National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. Montreal. May 2000. IPCC-XVI/Doc. 10 (1.IV.2000).

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Jacobs, G. (2010) Personal communication. Gwendolyn Jacobs, Energy Information Administration and Rubaab Bhangu, ICF International. *U.S. Territories Fossil Fuel Consumption, 1990–2009.* Unpublished. U.S. Energy Information Administration. Washington, DC.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates*. *Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration , U.S. Department of Energy. Washington, DC. June 22, 2001.

Mobile Combustion (excluding CO_2)

AAR (2009 through 2010) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, DC.

ANL (2006) Argonne National Laboratory (2006) GREET model Version 1.7. June 2006.

APTA (2007 through 2010) *Public Transportation Fact Book.* American Public Transportation Association, Washington, DC. Available online at <http://www.apta.com/research/stats/factbook/index.cfm>.

APTA (2006) *Commuter Rail National Totals.* American Public Transportation Association, Washington, DC. Available online at <http://www.apta.com/research/stats/rail/crsum.cfm>.

Benson, D. (2002 through 2004) Personal communication. Unpublished data developed by the Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

BEA (1991 through 2005) Unpublished BE-36 survey data. Bureau of Economic Analysis (BEA), U.S. Department of Commerce.

Browning, L. (2009) Personal communication with Lou Browning , “Suggested New Emission Factors for Marine Vessels.”, ICF International.

Browning, L. (2005) Personal communication with Lou Browning, Emission control technologies for diesel highway vehicles specialist, ICF International.

Browning, L. (2003) “VMT Projections for Alternative Fueled and Advanced Technology Vehicles through 2025.” 13th CRC On-Road Vehicle Emissions Workshop. April 2003.

DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.

DESC (2011) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, DC.

DOC (1991 through 2008) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, DC.

DOE (1993 through 2010) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-5198.

DOT (1991 through 2009) *Fuel Cost and Consumption*. Federal Aviation Administration, U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, DC. DAI-10.

EIA (2010) *Annual Energy Review 2009*. Energy Information Administration, U.S. Department of Energy, Washington, DC. July 2006. DOE/EIA-0384(2005).

EIA (2008a) "Table 3.1: World Petroleum Supply and Disposition." *International Energy Annual.* Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at <http://www.eia.doe.gov/iea/pet.html>.

EIA (2007a) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.* October 24, 2007.

EIA (2007b) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, December 2007,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2007/12).

EIA (2007 through 2009) *Natural Gas Annual*. Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0131(06).

EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov/fuelrenewable.html>.

EIA (1991 through 2011) *Fuel Oil and Kerosene Sales.* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0535-annual.

EPA (2008). "1970 - 2007 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. <http://www.epa.gov/ttn/chief/trends/index.html>

EPA (2007a) Annual Certification Test Results Report. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/otaq/crttst.htm>.

EPA (2007b) Confidential engine family sales data submitted to EPA by manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

EPA (2010a) Motor Vehicle Emission Simulator (MOVES). Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/otaq/ngm.htm>.

EPA (2010b*) NONROAD 2008a Model*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/oms/nonrdmdl.htm>.

EPA (2000) *Mobile6 Vehicle Emission Modeling Software*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

EPA (1999a) *Emission Facts: The History of Reducing Tailpipe Emissions.* Office of Mobile Sources. May 1999. EPA 420-F-99-017. Available online at <http://www.epa.gov/oms/consumer/f99017.pdf>.

EPA (1999b) Regulatory Announcement: EPA's Program for Cleaner Vehicles and Cleaner Gasoline. Office of Mobile Sources. December 1999. EPA420-F-99-051. Available online at <http://www.epa.gov/otaq/regs/ld-hwy/tier-2/frm/f99051.pdf>.

EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–1996*. Office of Mobile Sources, Assessment and Modeling Division, U.S. Environmental Protection Agency. August 1998. EPA420-R-98-009.

EPA (1997) *Mobile Source Emission Factor Model (MOBILE5a)*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.

EPA (1994a) *Automobile Emissions: An Overview.* Office of Mobile Sources. August 1994. EPA 400-F-92-007. Available online at <http://www.epa.gov/otaq/consumer/05-autos.pdf>.

EPA (1994b) *Milestones in Auto Emissions Control.* Office of Mobile Sources. August 1994. EPA 400-F-92-014. Available online at <http://www.epa.gov/otaq/consumer/12-miles.pdf>.

EPA (1993) *Automobiles and Carbon Monoxide.* Office of Mobile Sources. January 1993. EPA 400-F-92-005. Available online at <http://www.epa.gov/otaq/consumer/03-co.pdf>.

Esser, C. (2003 through 2004) Personal Communication with Charles Esser, Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.

FAA (2011) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). January 2011.

FAA (2009) *FAA Aerospace Forecasts Fiscal Years 2009–2025*. Table 30 "General Aviation Aircraft Fuel Consumption," Federal Aviation Administration. Available online at < http://www.faa.gov/data_research/aviation/aerospace_forecasts/2009-2025/media/Web%20GA%202009.xls>.

FAA (2006) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the System for Assessing Aviation's Global Emissions (SAGE). August 2006.

FHWA (1996 through 2010) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, DC. Report FHWA-PL-96-023-annual. Available online at <http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm>.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

ICF (2006a) *Revisions to Alternative Fuel Vehicle (AFV) Emission Factors for the U.S. Greenhouse Gas Inventory.* Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2006b) *Revised Gasoline Vehicle EFs for LEV and Tier 2 Emission Levels.* Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2004) *Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles*. Final Report to U.S. Environmental Protection Agency. February 2004.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Lipman, T. and M. Delucchi (2002) "Emissions of Nitrous Oxide and Methane from Conventional and Alternative Fuel Motor Vehicles." *Climate Change,* 53:477-516.

Unnasch, S., L. Browning, and E. Kassoy (2001) *Refinement of Selected Fuel-Cycle Emissions Analyses, Final Report to ARB.*

U.S. Census Bureau (2000) *Vehicle Inventory and Use Survey*. U.S. Census Bureau, Washington, DC. Database CD-EC97-VIUS.

Whorton, D. (2006 through 2010) Personal communication, Class II and III Rail energy consumption, American Short Line and Regional Railroad Association.

Carbon Emitted from Non-Energy Uses of Fossil Fuels

ACC (2011) "*Guide to the Business of Chemistry, 2011*," American Chemistry Council.

ACC (2003-2010) "PIPS Year-End Resin Statistics for 2010: Production, Sales and Captive Use," http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf

Bank of Canada (2011) Financial Markets Department Year Average of Exchange Rates. Available online at: http://www.bankofcanada.ca/rates/exchange/exchange-rates-in-pdf/?page_moved=1

EIA (2011) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, September 2011,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2011/09).

EIA (2010) *EIA Manufacturing Consumption of Energy (MECS) 2006,* U.S. Department of Energy, Energy Information Administration, Washington, DC.

EIA (2005) *EIA Manufacturing Consumption of Energy (MECS) 2002,* U.S. Department of Energy, Energy Information Administration, Washington, DC.

EIA (2001) *EIA Manufacturing Consumption of Energy (MECS) 1998,* U.S. Department of Energy, Energy Information Administration, Washington, DC.

EIA (1997) *EIA Manufacturing Consumption of Energy (MECS) 1994,* U.S. Department of Energy, Energy Information Administration, Washington, DC.

EIA (1994) *EIA Manufacturing Consumption of Energy (MECS) 1991,* U.S. Department of Energy, Energy Information Administration, Washington, DC.

EPA (2011) EPA's Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates http://www.epa.gov/oppbead1/pestsales/. Accessed January 2012.

EPA (2010). "1970 - 2009 Average annual emissions, all criteria pollutants in MS Excel." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards. <http://www.epa.gov/ttn/chief/trends/index.html>

EPA (2009) Biennial Reporting System (BRS) Database. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, DC. Available online at <http://www.epa.gov/enviro/html/brs/>. Data for 2001-2007 are current as of Sept. 9, 2009.

EPA (2007b) *Municipal Solid Waste in the United States: Facts and Figures for 2006*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>.

EPA (2006a) *Air Emissions Trends - Continued Progress Through 2005*. U.S. Environmental Protection Agency, Washington DC. December 19, 2006. < http://www.epa.gov/air/airtrends/index.html>

EPA (2004) EPA's Pesticides Industry Sales and Usage, 2000 and 2001 Market Estimates http://www.epa.gov/oppbead1/pestsales/. Accessed September 2006.

EPA (2002) EPA's Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates, table 3.6. (http://www.epa.gov/oppbead1/pestsales/99pestsales/market_estimates1999.pdf). Accessed July 2003.

EPA (2001) AP 42, Volume I, Fifth Edition. Chapter 11: Mineral Products Industry. Available online at http://www.epa.gov/ttn/chief/ap42/ch11/index.html

EPA (2000a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, DC. Available online at <http://www.epa.gov/enviro/html/brs/>.

EPA (2000b) *Toxics Release Inventory, 1998*. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, DC. Available online at <http://www.epa.gov/triexplorer/chemical.htm>.

EPA (1999) EPA's Pesticides Industry Sales and Usage, 1996-1997 Market Estimates and http://www.epa.gov/oppbead1/pestsales/97pestsales/market_estimates1997.pdf.

EPA (1998) EPA's Pesticides Industry Sales and Usage, 1994-1995 Market Estimates http://www.epa.gov/oppbead1/pestsales/95pestsales/market_estimates1995.pdf.

FEB (2011) *Fiber Economics Bureau, as cited in C&EN (2011) Output Ramps up in all Regions*. Chemical Engineering News, American Chemical Society, 4 July. Available online at http://www.cen-online.org.

FEB (2010) *Fiber Economics Bureau, as cited in C&EN (2010) Output Declines in U.S., Europe*. Chemical & Engineering News, American Chemical Society, 6 July. Available online at <http://www.cen-online.org>.

FEB (2009) *Fiber Economics Bureau, as cited in C&EN (2009) Chemical Output Slipped In Most Regions* Chemical & Engineering News, American Chemical Society, 6 July. Available online at <http://www.cen-online.org>.

FEB (2007) *Fiber Economics Bureau, as cited in C&EN (2007) Gains in Chemical Output Continue*. Chemical &

Engineering News, American Chemical Society. July 2, 2007. Available online at <http://www.cen-online.org>.

FEB (2005) *Fiber Economics Bureau, as cited in C&EN (2005) Production: Growth in Most Regions* Chemical & Engineering News, American Chemical Society, 11 July. Available online at http://www.cen-online.org.

FEB (2003) *Fiber Economics Bureau, as cited in C&EN (2003) Production Inches Up in Most Countries,* Chemical & Engineering News, American Chemical Society, 7 July. Available online at http://www.cen-online.org.

FEB (2001) *Fiber Economics Bureau, as cited in ACS (2001) Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole* Chemical & Engineering News, American Chemical Society, 25 June. Available online at http://pubs.acs.org/cen

Financial Planning Association (2006) Canada/US Cross-Border Tools: US/Canada Exchange Rates. Available online at: http://www.fpanet.org/global/planners/US_Canada_ex_rates.cfm. Accessed August 16, 2006.

Gosselin, Smith, and Hodge (1984), "Clinical Toxicology of Commercial Products." Fifth Edition, Williams & Wilkins, Baltimore.

Huurman, J.W.F. (2006) R*ecalculation of Dutch Stationary Greenhouse Gas Emissions Based on Sectoral Energy Statistics 1990-2002*. Statistics Netherlands, Voorburg, The Netherlands.

IISRP (2003) "*IISRP Forecasts Moderate Growth in North America to 2007*" International Institute of Synthetic Rubber Producers, Inc. New Release; available online at: <http://www.iisrp.com/press-releases/2003-Press-Releases/IISRP-NA-Forecast-03-07.html>.

IISRP (2000) "Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA" International Institute of Synthetic Rubber Producers press release.

INEGI (2006) Producción bruta total de las unidades económicas manufactureras por Subsector, Rama, Subrama y Clase de actividad. http://www.inegi.gob.mx/est/contenidos/espanol/proyectos/censos/ce2004/tb_manufacturas.asp. Accessed August 15.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Marland, G., and R.M. Rotty (1984), “Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982”, Tellus 36b:232-261.

NPRA (2002) North American Wax - A Report Card <http://www.npra.org/members/publications/papers/lubes/LW-02-126.pdf>

RMA (2009a). *Scrap Tire Markets in the United States: 9th Biennial Report*. Rubber Manufacturers Association, Washington, DC. May 2009.

RMA (2009b) “Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics.” Available online at: http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/ Accessed 17 September 2009.Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

U.S. Bureau of the Census (2009) *Soap and Other Detergent Manufacturing: 2007*. Available online at <http://smpbff1.dsd.census.gov/TheDataWeb_HotReport/servlet/HotReportEngineServlet?emailname=vh@boc&filename=mfg1.hrml&20071204152004.Var.NAICS2002=325611&forward=20071204152004.Var.NAICS2002 >.

U.S. Bureau of the Census (2004) *Soap and Other Detergent Manufacturing: 2002*, Issued December 2004, EC02-31I-325611 (RV). Available online at <http://www.census.gov/prod/ec02/ec0231i325611.pdf>.

U.S. Bureau of the Census (1999) *Soap and Other Detergent Manufacturing: 1997,* Available online at < http://www.census.gov/epcd/www/ec97stat.htm>.

U.S. International Trade Commission (1990-2011) “Interactive Tariff and Trade DataWeb: Quick Query.” Available online at: http://dataweb.usitc.gov/ Accessed October 2011.

Incineration of Waste

ArSova, Ljupka, Rob van Haaren, Nora Goldstein, Scott M. Kaufman, and Nickolas J. Themelis (2008). “16th Annual BioCycle Nationwide Survey: The State of Garbage in America” Biocycle, JG Press, Emmaus, PA. December.

Bahor, B (2009) Covanta Energy’s public review comments re: *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007.* Submitted via email on April 9, 2009 to Leif Hockstad, U.S. EPA.

De Soete, G.G. (1993) “Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control.” In A. R. Van Amstel, (ed) Proc. of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort, NL. February 3-5, 1993.

Energy Recovery Council (2009). “2007 Directory of Waste-to-Energy Plants in the United States,” accessed September 29, 2009.

EPA (2011a) Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2010. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, DC. Available online at <http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>.

EPA (2007, 2008, 2011b) Municipal Solid Waste in the United States: Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, DC. Available online at <http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>.

EPA (2006) Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, DC.

EPA (2000) Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, DC. EPA530-F-00-024.

Goldstein, N. and C. Madtes (2001) “13th Annual BioCycle Nationwide Survey: The State of Garbage in America.” BioCycles, JG Press, Emmaus, PA. December 2001.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Kaufman, et al. (2004) “14th Annual BioCycle Nationwide Survey: The State of Garbage in America 2004” Biocycle, JG Press, Emmaus, PA. January, 2004.

RMA (2012a) “Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics.” Available online at: <http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/> Accessed 18 January 2012.

RMA (2012b) "Rubber FAQs." Rubber Manufacturers Association. Available online at: http://www.rma.org/about_rma/rubber_faqs/ Accessed 18 January 2012.

RMA (2011) “U.S. Scrap Tire Management Summary 2005-2009.” Rubber Manufacturers Association. October 2011. Available online at: <http://www.rma.org/scrap_tires/scrap_tire_markets/2009_summary.pdf>

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

Simmons, et al. (2006) “15th Nationwide Survey of Municipal Solid Waste Management in the United States: The State of Garbage in America” BioCycle, JG Press, Emmaus, PA. April 2006.

van Haaren, Rob, Thermelis, N., and Goldstein, N. (2010) "The State of Garbage in America." BioCycle, October 2010. Volume 51, Number 10, pg. 16-23.

Coal Mining

AAPG (1984) *Coalbed Methane Resources of the United States.* AAPG Studies in Geology Series #17.

DOE (1983) *Methane Recovery from Coalbeds: A Potential Energy Source*. U.S. Department of Energy. DOE/METC/83-76.

EIA (2010) *Annual Coal Report 1991-2009 (*Formerly called *Coal Industry Annual)*. Table 1. Energy Information Administration, U.S. Department of Energy,Washington, DC.

EPA (1996) *Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States*. U.S. Environmental Protection Agency. EPA/600/R-96-065.

GRI (1988) *A Geologic Assessment of Natural Gas from Coal Seams.* Topical Reports, Gas Research Institute 1986-88.

Mutmansky, Jan M. and Yanbei Wang (2000) "Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions." *Mineral Resources Engineering,* 9(4). December 2000.

USBM (1986) *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*. Circular 9067, U.S. Bureau of Mines.

Abandoned Underground Coal Mines

EPA (2003) *Methane Emissions Estimates & Methodology for Abandoned Coal Mines in the U.S.* Draft Final Report. Washington, DC. June 2003.

Mutmansky, Jan M., and Yanbei Wang (2000) *Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions.* Department of Energy and Geo-Environmental Engineering, Pennsylvania State University. University Park, PA.

U.S. Department of Labor, Mine Health & Safety Administration (2011) *Data Retrieval System*. Available online at <http://www.msha.gov/drs/drshome.htm>.

Natural Gas Systems

AAPG (2004) Shale Gas Exciting Again. American Association of Petroleum Geologists. Available online at <http://www.aapg.org/explorer/2001/03mar/gas_shales.html>.

AGA (1991 through 1998) Gas Facts. American Gas Association. Washington, DC.

API (2005) "Table 12—Section III—Producing Oil Wells in the United States by State." In *Basic Petroleum Data Book.* American Petroleum Institute, Volume XXV, Number 1. February 2005.

Alabama (2010) Alabama State Oil and Gas Board. Available online at <http://www.ogb.state.al.us>.

BOEMRE (2010a) Gulf of Mexico Region Offshore Information. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/offshore/fldresv/resvmenu.html>.

BOEMRE (2010b) Gulf of Mexico Region Products/Free Data. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/pubinfo/freeasci/platform/freeplat.html>.

BOEMRE (2010c) OCS Platform Activity. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior. Available online at <http://www.mms.gov/stats>.

BOEMRE (2010d) Pacific OCS Region. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior. Available online at <http://www.gomr.mms.gov/homepg/pubinfo/pacificfreeasci/platform/pacificfreeplat.html>.

BOEMRE (2004) *Gulfwide Emission Inventory Study for the Regional Haze and Ozone Modeling Effort.* OCS Study MMS 2004-072.

Brookhaven (2004) Natural Gas Field Subject of Interest at Brookhaven College. Brookhaven College. Available online at <http://www.brookhavencollege.edu/news/2004/news1752.html>.

EIA (2010a) Number of Producing Gas and Gas Condensate Wells, 1989-2009, Natural Gas Navigator. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2010b) "Table 1—Summary of Natural Gas Supply and Disposition in the United States 1999-2010." Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

E
A

EIA (2010d) Table 5.2. Monthly Energy Review. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov/emeu/mer/resource.html>.

EIA (2010e) “Table 6—Marketed Production of Natural Gas by State.” Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2010f) U.S. Imports by Country. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://www.eia.doe.gov>.

EIA (2005) “Table 5—U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 1977-2003.” Energy Information Administration, Department of Energy, Washington, DC.

EIA (2004) *US LNG Markets and Uses*. Energy Information Administration, U.S. Department of Energy, Washington, DC. June 2004. Available online at <http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2004/lng/lng2004.pdf>.

EIA (2001) “Documentation of the Oil and Gas Supply Module (OGSM).” Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at <http://tonto.eia.doe.gov/FTPROOT/modeldoc/m063(2001).pdf>.

EIA (1996) “Emissions of Greenhouse Gases in the United States” Carbon Dioxide Emissions. Energy Information Administration, U.S. Department of Energy, Washington, DC.

EPA (2010) Natural Gas STAR Reductions 1990-2009. Natural Gas STAR Program.

EPA (2007) *Reducing Methane Emissions During Completions Operations*. Natural Gas STAR Producer’s Technology Transfer Workshop. September 11, 2007. <http://epa.gov/gasstar/documents/workshops/glenwood-2007/04_recs.pdf>.

EPA (2006a) *Installing Plunger Lift Systems in Gas Wells*. Lessons Learned from Natural Gas STAR Partners. October 2006. <http://epa.gov/gasstar/documents/ll_plungerlift.pdf>.

EPA (2006b) *Replacing Wet Seals with Dry Seals in Centrifugal Compressors*. Lessons Learned from Natural Gas STAR Partners. October 2006. <http://epa.gov/gasstar/documents/ll_wetseals.pdf>.

EPA (2004) *Green Completions* Natural Gas STAR Producer’s Technology Transfer Workshop. September 21, 2004. <http://epa.gov/gasstar/workshops/techtransfer/2004/houston-02.html>.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report).* Prepared by ICF-Kaiser, Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA/GRI (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

FERC (2010). *North American LNG Terminals* . Federal Energy Regulatory Commission, Washington, DC. Available online at <http://www.ferc.gov/industries/lng/indus-act/terminals/lng-existing.pdf>.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

HPDI (2009) Production and Permit Data, October 2009.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, H.S. Eggleston, L. Buenida, K. Miwa, T Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). Hayama, Kanagawa, Japan.

Kansas (2010) Kansas Geological Survey. Oil and Gas Production Data, All Wells, University of Kansas. Available online at <http://www.kgs.ku.edu/PRS/petroDB.html>.

Lippman (2003) Rocky Mountain Region Second Quarter 2003 Production Report. Lippman Consulting, Inc.

Montana (2010) Montana Online Oil and Gas Information System. Montana Board of Oil and Gas Conservation, Billing Office. Available online at <http://bogc.dnrc.state.mt.us/jdpIntro.htm>.

Morgan Stanley (2005) Barnett Shale Update: None-Core Confidence Rises. Available online at <http://www.endevcoinc.com/technical%20papers/Morgan%20Stanley%20Outlook%20on%20Barnett%20 Shale.pdf>.

New Mexico (2010) Annual Gas Well Counts by State District. Available online at <http://www.emnrd.state.nm.us/ocd/>.

New Mexico (2005) Districts. Available online at <http://www.emnrd.state.nm.us/ocd/districts.htm>.

OGJ (1997-2010) "Worldwide Gas Processing." *Oil & Gas Journal,* PennWell Corporation, Tulsa, OK.

Oklahoma (2010) Oklahoma Petroleum Information Center—Coalbed-Methane Completions database. Oklahoma Geological Survey. Available online at <http://www.ogs.ou.edu/homepage.php>.

OPS (2010a) Natural Gas Transmission Pipeline Annual Mileage. Office of Pipeline Safety, U.S. Department of Transportation, Washington, DC. Available online at <http://ops.dot.gov/stats/stats.htm>.

OPS (2010b) Distribution Annuals Data. Office of Pipeline Safety, U.S. Department of Transportation, Washington, DC. Available online at <http://ops.dot.gov/stats/stats.htm>.

TERC (2009) *VOC Emissions from Oil and Condensate Storage Tanks*. Hendler, Albert, URS Corporation; Nunn, Jim, COMM Engineering; Lundeen, Joe, Trimeric Corporation. Revised April 2, 2009. Available online at: <http://files.harc.edu/Projects/AirQuality/Projects/H051C/H051CFinalReport.pdf>.

Texas (2010a) Gas Well Counts by County. Texas Railroad Commission. Available online at <http://www.rrc.state.tx.us/data/index.php>.

Texas (2010b) Oil Well Counts by County. Texas Railroad Commission. Available online at <http://www.rrc.state.tx.us/data/index.php>.

Texas (2010c) *The Barnett Shale Regional Report*. Foster, Brad, Devon Energy, Texas Railroad Commission. Available online at <http://www.rrc.state.tx.us/data/index.php>.

Texas (2010d) Oil and Gas District Boundaries. Texas Railroad Commission. Available online at <http://www.rrc.state.tx.us/divisions/og/ogmap.html>.

Utah (2010) Oil and Gas Data Download. Utah Division of Oil, Gas and Mining—Department of Natural Resources. Available online at <http://ogm.utah.gov/oilgas/DOWNLOAD/downpage.htm>.

WGC (2009) "Methane's Role in Promoting Sustainable Development in the Oil and Natural Gas Industry." October 2009.

World Oil Magazine (2010a) "Outlook 2009: Producing Gas Wells." 228(2). February 2010. Available online at <http://www.worldoil.com>.

World Oil Magazine (2010b) "Outlook 2009: Producing Oil Wells." 228(2). February 2010. Available online at <http://www.worldoil.com>.

Wyoming (2010) Wyoming Oil and Gas Conservation Commission. Available online at <http://wogcc.state.wy.us/coalbedchart.cfm>.

Petroleum Systems

API (2009) Compendium of Greenhouse gas Emissions Methodologies for the Oil and Gas Industry. American Petroleum Institute. Austin, TX, August 2009.

BOEMRE (2011a) *OCS Platform Activity.* Bureau of Ocean Energy Management, Regulation, and Enforcement, U.S. Department of Interior. Available online at <http://www.boemre.gov/stats/>.

BOEMRE (2011b) *Platform Information and Data.* Bureau of Ocean Energy Management, Regulation, and Enforcement, U.S. Department of Interior. Available online at <http://www.gomr.boemre.gov/homepg/pubinfo/freeasci/platform/freeplat.html>.

BOEMRE (2011c) *Pacific OCS Region*. Bureau of Ocean Energy Management, Regulation, and Enforcement, U.S. Department of Interior. Available online at <http://www.gomr.boemre.gov/homepg/pubinfo/pacificfreeasci/platform/pacificfreeplat.html>.

BOEMRE (2005) *Field and Reserve Information.* Bureau of Ocean Energy Management, Regulation, and Enforcement, U.S. Department of Interior. Available online at < http://www.gomr.boemre.gov/homepg/offshore/fldresv/resvmenu.html >.

BOEMRE (2004). *Gulfwide Emission Inventory Study for the Regional Haze and Ozone Modeling Effort.* Bureau of Ocean Energy Management, Regulation, and Enforcement (formerly Minerals Management Service), U.S. Department of Interior. OCS Study MMS 2004-072.

EIA (1990 through 2010) *Refinery Capacity Report*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at <http://www.eia.doe.gov/oil_gas/petroleum/data_publications/refinery_capacity_data/refcapacity.html>.

EIA (1995 through 2010a) *Annual Energy Review*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at <http://www.eia.doe.gov/emeu/aer/contents.html>.

EIA (1995 through 2010b) *Monthly Energy Review*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at <http://www.eia.doe.gov/emeu/mer>.

EIA (1995 through 2010) *Petroleum Supply Annual. Volume 1.* U.S Department of Energy Washington, DC. Available online at: <http://www.eia.doe.gov/oil_gas/petroleum/data_publications/petroleum_supply_annual/psa_volume1/psa_volume1.html>

EPA (2005) *Incorporating the Mineral Management Service Gulfwide Offshore Activities Data System (GOADS) 2000 data into the methane emissions inventories*. Prepared by ICF International. U.S. Environmental Protection Agency. 2005.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report).* Prepared by ICF International. Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA (1996) *Methane Emissions from the U.S. Petroleum Industry (Draft)*. Prepared by Radian. U.S. Environmental Protection Agency. June 1996.

EPA (1995) *Compilation of Air Pollutant Emission Factors AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources.* U.S. Environmental Protection Agency. Available online at <http://www.epa.gov/ttn/chief/ap42/index.html>.

EPA/GRI (1996a) *Methane Emissions from the Natural Gas Industry, V7: Blow and Purge Activities*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996b) *Methane Emissions from the Natural Gas Industry, V11: Compressor Driver Exhaust*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996c) *Methane Emissions from the Natural Gas Industry, V12: Pneumatic Devices*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996d) *Methane Emissions from the Natural Gas Industry, V13: Chemical Injection Pumps*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

HPDI (2011) Production and Permit Data, October 2009.

IOGCC (2009) *Marginal Wells: fuel for economic growth 2008 Report*. Interstate Oil & Gas Compact Commission. Available online at <http://iogcc.myshopify.com/>.

OGJ (2010a) *Oil and Gas Journal 1990-2009.* Pipeline Economics Issue, November 2010.

OGJ (2010b) *Oil and Gas Journal 1990-2009.* Worldwide Refining Issue, January 2010.

TERC (2009) *VOC Emissions from Oil and Condensate Storage Tanks*. Hendler, Albert, URS Corporation; Nunn, Jim, COMM Engineering; Lundeen, Joe, Trimeric Corporation. Revised April 2, 2009. Available online at: <http://files.harc.edu/Projects/AirQuality/Projects/H051C/H051CFinalReport.pdf>.

United States Army Corps of Engineers (1995-2009) *Waterborne Commerce of the United States, Part 5: National Summaries*. U.S. Army Corps of Engineers. Washington, DC.

Energy Sources of Indirect Greenhouse Gases

EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

EPA (2009). "1970 - 2008 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

International Bunker Fuels

ASTM (1989) *Military Specification for Turbine Fuels, Aviation, Kerosene Types*, NATO F-34 (JP-8) and NATO F-35. February 10, 1989. Available online at <http://test.wbdg.org/ccb/FEDMIL/t_83133d.pdf>.

Chevron (2000) *Aviation Fuels Technical Review (FTR-3)*. Chevron Products Company, Chapter 2. Available online at <http://www.chevron.com/products/prodserv/fuels/bulletin/aviationfuel/2_at_fuel_perf.shtm>

DESC (2011) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, DC.

DHS (2008). Personal Communication with Elissa Kay, Residual and Distillate Fuel Oil Consumption (International Bunker Fuels). Department of Homeland Security, Bunker Report. January 11, 2008.

DOC (2011) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, DC.

EIA (2011a) *Annual Energy Review 2010*. Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0384(2011). October 19, 2011.

EIA (2011b) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, September 2011,* Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2011/09).

FAA (2010) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). January 2010.

FAA (2006). *System for assessing Aviation's Global Emission (SAGE) Model*. Federal Aviation Administration's Office of Aviation Policy, Planning, and Transportation Topics, 2006.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

USAF (1998) *Fuel Logistics Planning.* U.S. Air Force pamphlet AFPAM23-221, May 1, 1998.

Wood Biomass and Ethanol Consumption

EIA (2011) *Annual Energy Review 2010*. Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0384 (2010). October 19, 2011.

EPA (2011). Acid Rain Program Dataset 1996-2010. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2010). Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and

Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Industrial Processes

Cement Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

U.S. Bureau of Mines (1990 through 1993) *Minerals Yearbook: Cement Annual Report.* U.S. Department of the Interior, Washington, DC.

USGS (1995 through 2011) *Mineral Commodity Summaries - Cement*. U.S. Geological Survey, Reston, VA.

Van Oss (2008) Personal communication. Hendrik van Oss, Commodity Specialist of the U.S. Geological Survey and Erin Gray, ICF International. December 16, 2008.

Lime Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. , National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. Montreal. May 2000. IPCC-XVI/Doc. 10 (1.IV.2000).

Lutter (2009 through 2010). Personal communication. Karen Lutter, California Air Resources Board and Mausami Desai, EPA. October 20, 2009; September 28, 2010.

Males, E. (2003) Memorandum from Eric Males, National Lime Association to Mr. William N. Irving & Mr. Leif Hockstad, Environmental Protection Agency. March 6, 2003.

Miner, R. and B. Upton (2002). Methods for estimating greenhouse gas emissions from lime kilns at kraft pulp mills. Energy. Vol. 27 (2002), p. 729-738.

Prillaman (2008 through 2010). Personal communication. Hunter Prillaman, National Lime Association and Mausami Desai, EPA. November 5, 2008; October 19, 2009; October 21, 2010.

USGS (1992 through 2011) *Minerals Yearbook: Lime*. U.S. Geological Survey, Reston, VA.

Limestone and Dolomite Use

U.S. Bureau of Mines (1991 & 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, DC.

U.S. Bureau of Mines (1990 through 1993b) *Minerals Yearbook: Magnesium and Magnesium Compounds Annual Report*. U.S. Department of the Interior. Washington, DC.

USGS (1995 through 2011a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995 through 2011b) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA.

Soda Ash Production and Consumption

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

USGS (1994 through 2011) Minerals Yearbook: Soda Ash Annual Report. U.S. Geological Survey, Reston, VA.

Ammonia Production and Urea Consumption

Bark (2004) *CoffeyvilleNitrogen Plant* Available online at <http://www.gasification.org/Docs/2003_Papers/07BARK.pdf> December 15, 2004.

Coffeyville Resources Nitrogen Fertilizers (2011). Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Coffeyville Resources Nitrogen Fertilizers (2010). Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Coffeyville Resources Nitrogen Fertilizers (2009). Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>.

Coffeyville Resources Nitrogen Fertilizers, LLC (2005 through 2007a) Business Data. Available online at <http://www.coffeyvillegroup.com/businessSnapshot.asp>

Coffeyville Resources Nitrogen Fertilizers (2007b). Nitrogen Fertilizer Operations. Available online at <http://coffeyvillegroup.com/nitrogenMain.aspx>.

EEA (2004) *Natural Gas Issues for the U.S. Industrial and Power Generation Sectors*. Submitted to National Commission on Energy Policy.

EIA (2011) *Natural Gas Prices for the U.S. 2005-2010* <http://205.254.135.24/dnav/ng/ng_pri_sum_dcu_nus_a.htm>

EFMA (2000) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate.

EFMA (1995) *Production of Ammonia.* European Fertilizer Manufacturers Association. March 1, 1995.

TFI (2002) *U.S. Nitrogen Imports/Exports Table.* The Fertilizer Institute. Available online at <http://www.tfi.org/statistics/usnexim.asp>. August 2002.

TIG (2002) *Chemical Profiles – Urea*. The Innovation Group. Available online at <http://www.the-innovation-group.com/ChemProfiles/Urea.htm>. September 2007.

U.S. Bureau of the Census (2011), *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Bureau of the Census (2010), *Current Industrial Reports Fertilizer Materials and Related Products: 2009 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Bureau of the Census (2009), *Current Industrial Reports Fertilizer Materials and Related Products: 2008 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Bureau of the Census (2008), *Current Industrial Reports Fertilizer Materials and Related Products: 2007 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b/mq325b075.xls.>

U.S. Census Bureau (2007) *Current Industrial Reports Fertilizer Materials and Related Products: 2006 Summary*. Available online at < http://www.census.gov/industry/1/mq325b065.pdf>.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer Materials and Related Products: 2005 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2002, 2004, 2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1998 through 2002b, 2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2002a) *Current Industrial Reports Fertilizer Materials and Related Products: First Quarter 2002*. June 2002. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2002c) *Current Industrial Reports Fertilizer Materials and Related Products: Third Quarter 2001*. January 2002. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2001a) *Current Industrial Reports Fertilizer Materials and Related Products: Second Quarter 2001*. September 2001. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1991 through 1994) *Current Industrial Reports Fertilizer Materials Annual Report.* Report No. MQ28B. U.S. Census Bureau, Washington, DC.

U.S. Department of Agriculture (2011) Economic Research Service Data Sets, Data Sets, U.S. Fertilizer Imports/Exports: Standard Tables. Available online at <http://www.ers.usda.gov/Data/FertilizerTrade/standard.htm>.

USGS (1994 through 2009) Minerals Yearbook: Nitrogen. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>.

U.S. ITC (2002) *United States International Trade Commission Interactive Tariff and Trade DataWeb, Version 2.5.0*. Available online at <http://dataweb.usitc.gov/scripts/user_set.asp>. August 2002.

Urea Consumption for Non-Agricultural Purposes

EFMA (2000) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

TFI (2002) *U.S. Nitrogen Imports/Exports Table.* The Fertilizer Institute. Available online at <http://www.tfi.org/statistics/usnexim.asp>. August 2002.

U.S. Bureau of the Census (2011), *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Bureau of the Census (2010), *Current Industrial Reports Fertilizer Materials and Related Products: 2009 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Bureau of the Census (2009), *Current Industrial Reports Fertilizer Materials and Related Products: 2008 Summary.* Available online at <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html.

U.S. Bureau of the Census (2008), *Current Industrial Reports Fertilizer Materials and Related Products: 2007 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b/mq325b075.xls.>

U.S. Census Bureau (2007) *Current Industrial Reports Fertilizer Materials and Related Products: 2006 Summary*. Available online at < http://www.census.gov/industry/1/mq325b065.pdf>.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer Materials and Related Products: 2005 Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2002, 2004, 2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (1998 through 2002b, 2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports Summary*. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2002a) *Current Industrial Reports Fertilizer Materials and Related Products: First Quarter 2002*. June 2002. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2002c) *Current Industrial Reports Fertilizer Materials and Related Products: Third Quarter 2001*. January 2002. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Census Bureau (2001a) *Current Industrial Reports Fertilizer Materials and Related Products: Second Quarter 2001*. September 2001. Available online at <http://www.census.gov/cir/www/325/mq325b.html>.

U.S. Department of Agriculture (2011) Economic Research Service Data Sets, Data Sets, U.S. Fertilizer Imports/Exports: Standard Tables. Available online at <http://www.ers.usda.gov/Data/FertilizerTrade/standard.htm>.

USGS (1994 through 2009) Minerals Yearbook: Nitrogen. Available online at

<http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>.

U.S. ITC (2002) *United States International Trade Commission Interactive Tariff and Trade DataWeb, Version 2.5.0*. Available online at <http://dataweb.usitc.gov/scripts/user_set.asp>. August 2002.

Nitric Acid Production

Desai (2012) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Paul Stewart, ICF International, January 25, 2012.

EPA (2010) *Draft Nitric Acid Database.* U.S. Environmental Protection Agency, Office of Air and Radiation. September, 2010.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

US Census Bureau (2011) *Current Industrial Reports. Fertilizers and Related Chemicals: 2010.* "Table 1: Summary of Production of Principle Fertilizers and Related Chemicals: 2009 and 2010." June, 2011. MQ325B(10)-5. Available online at < http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

US Census Bureau (2010a) *Current Industrial Reports. Fertilizers and Related Chemicals: 2009.* "Table 1: Summary of Production of Principle Fertilizers and Related Chemicals: 2009 and 2008." June, 2010. MQ325B(08)-5. Available online at < http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

US Census Bureau (2010b) Personal communication between Hilda Ward (of U.S. Census Bureau) and Caroline Cochran (of ICF International). October 26, 2010 and November 5, 2010.

US Census Bureau (2009) *Current Industrial Reports. Fertilizers and Related Chemicals: 2008.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2004 to 2008." June, 2009. MQ325B(08)-5. Available online at < http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

US Census Bureau (2008) *Current Industrial Reports. Fertilizers and Related Chemicals: 2007.* "Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2003 to 2007." June, 2008. MQ325B(07)-5. Available online at < http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html >.

US Census Bureau (2006) *Current Industrial Reports.*, "Table 995: Inorganic Chemicals and Fertilizers." August, 2006. Series MAQ325A Available online at <www.census.gov/compendia/statab/2007/tables/07s0995.xls>.

Adipic Acid Production

ACC (2011) "Business of Chemistry (Annual Data).xls." American Chemistry Council Guide to the Business of Chemistry. August 2011.

C&EN (1995) "Production of Top 50 Chemicals Increased Substantially in 1994." *Chemical & Engineering News*, 73(15):17. April 10, 1995.

C&EN (1994) "Top 50 Chemicals Production Rose Modestly Last Year." *Chemical & Engineering News*, 72(15):13. April 11, 1994.

C&EN (1993) "Top 50 Chemicals Production Recovered Last Year." *Chemical & Engineering News*, 71(15):11. April 12, 1993.

C&EN (1992) "Production of Top 50 Chemicals Stagnates in 1991." *Chemical & Engineering News*, 70(15): 17. April 13, 1992.

CMR (2001) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. July 16, 2001.

CMR (1998) "Chemical Profile: Adipic Acid." *Chemical Market Reporter*. June 15, 1998.

CW (2007) "Product Focus: Adipic Acid." *Chemical Week*. August 1-8, 2007.

CW (2005) "Product Focus: Adipic Acid." *Chemical Week*. May 4, 2005.

CW (1999) "Product Focus: Adipic Acid/Adiponitrile." *Chemical Week*, p. 31. March 10, 1999.

Desai (2012) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Toby Mandel, ICF International, January 25, 2012.

Desai (2010) Personal communication. Mausami Desai, U.S. Environmental Protection Agency, and Caroline Cochran, ICF International. November 8, 2010.

Desai (2009) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Joseph Herr, ICF International. November 19, 2009.

ICIS (2007) "Adipic Acid." *ICIS Chemical Business Americas*. July 9, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A. and Triner, V.G. (1999) "Implementation of Technologies for Abatement of N_2O Emissions Associated with Adipic Acid Manufacture." Proceedings of the 2nd Symposium on Non-CO_2 Greenhouse Gases (NCGG-2), Noordwijkerhout, The Netherlands, 8-10 Sept. 1999, Ed. J. van Ham *et al*., Kluwer Academic Publishers, Dordrecht, pp. 347-358.

SEI (2010) *Industrial N_2O Projects Under the CDM: Adipic Acid – A Case for Carbon Leakage?* Stockholm Environment Institute Working Paper WP-US-1006. October 9, 2010.

Thiemens, M.H., and W.C. Trogler (1991) "Nylon production; an unknown source of atmospheric nitrous oxide." *Science* 251:932-934.

VA DEQ (2010) Personal communication. Stanley Faggert, Virgina Department of Environmental Quality and Joseph Herr, ICF International. March 12, 2010.

VA DEQ (2009) Personal communication. Stanley Faggert, Virgina Department of Environmental Quality and Joseph Herr, ICF International. October 26, 2009.

VA DEQ (2006) Virginia Title V Operating Permit. Honeywell International Inc. Hopewell Plant. Virginia Department of Environmental Quality. Permit No. PRO50232. Effective January 1, 2007.

Silicon Carbide Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, eds.; Institute for Global Environmental Strategies (IGES). Hayama, Kanagawa, Japan.

U.S. Census Bureau (2005 through 2011) *U.S International Trade Commission (USITC) Trade DataWeb.* Available online at <http://dataweb.usitc.gov/>.

USGS (2011a) *Minerals Commodity Summary: Abrasives (Manufactured) 2009.* U.S. Geological Survey, Reston, VA.

USGS (1991a through 2010a and 2011b) *Minerals Yearbook: Manufactured Abrasives Annual Report.* U.S. Geological Survey, Reston, VA.

USGS (1991b through 2010b and 2011c) *Minerals Yearbook: Silicon Annual Report.* U.S. Geological Survey, Reston, VA.

Petrochemical Production

ACC (2002, 2003, 2005 through 2011) *Guide to the Business of Chemistry.* American Chemistry Council, Arlington, VA.

EIA (2004) *Annual Energy Review 2003*. Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0384(2003). September 2004.

EIA (2003) *Emissions of Greenhouse Gases in the United States 2002.* Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE-EIA-0573(2002). February 2003.

European IPPC Bureau (2004) *Draft Reference Document on Best Available Techniques in the Large Volume Inorganic Chemicals—Solid and Others Industry,* Table 4.21. European Commission, 224. August 2004.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Jordan, J. (2011a) Personal communication, Jim Jordan of Jordan Associates on behalf of the Methanol Institute and Pier LaFarge, ICF International. October 19th, 2011

Jordan, J. (2011b) Personal communication, Jim Jordan of Jordan Associates on behalf of the Methanol Institute and Pier LaFarge, ICF International. October 18th, 2011

Johnson, G. L. (2011) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Pier LaFarge, ICF International. October 2011.

Johnson, G. L. (2010) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caroline Cochran, ICF International. September 2010.

Johnson, G. L. (2009) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Jean Y. Kim, ICF International. October 2009.

Johnson, G. L. (2008) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Jean Y. Kim, ICF International. November 2008.

Johnson, G. L. (2007) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Tristan Kessler, ICF International. November 2007.

Johnson, G. L. (2006) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Erin Fraser, ICF International. October 2006.

Johnson, G. L. (2005) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Erin Fraser, ICF International. October 2005.

Johnson, G. L. (2003) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caren Mintz, ICF International November 2003.

Othmer, K. (1992) Carbon (*Carbon Black*), Vol. 4, 1045.

Srivastava, Manoj, I.D. Singh, and Himmat Singh (1999) "Structural Characterization of Petroleum Based Feedstocks for Carbon Black Production," Table-1. *Petroleum Science and Technology* 17(1&2):67-80.

The Innovation Group (2004) *Carbon Black Plant Capacity*. Available online at <http://www.the-innovation-group.com/ChemProfiles/Carbon%20Black.htm>.

U.S. Census Bureau (2007) 2006 *Economic Census: Manufacturing—Industry Series: Carbon Black Manufacturing*. Department of Commerce. Washington, DC. EC0731I3. June 2009.

U.S. Census Bureau (2004) 2002 *Economic Census: Manufacturing—Industry Series: Carbon Black Manufacturing*. Department of Commerce. Washington, DC. EC02-311-325182. September 2004.

U.S. Census Bureau (1999) *1997 Economic Census: Manufacturing—Industry Series: Carbon Black Manufacturing*. Department of Commerce. Washington, DC. EC97M-3251F. August 1999.

Titanium Dioxide Production

Gambogi, J. (2002) Telephone communication. Joseph Gambogi, Commodity Specialist, U.S. Geological Survey and Philip Groth, ICF International. November 2002.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nelson, H.W. (1969) *Petroleum Coke Handling Problems*. Great Lakes Carbon Corporation.

USGS (2011a) *Mineral Commodity Summary: Titanium 2010*. U.S. Geological Survey, Reston, VA.

USGS (USGS 1991 through 2011b) *Mineral Yearbook: Titanium Annual Report.* U.S. Geological Survey, Reston, VA.

Carbon Dioxide Consumption

Allis, R. et al. (2000) *Natural CO_2 Reservoirs on the Colorado Plateau and Southern Rocky Mountains: Candidates for CO_2 Sequestration*. Utah Geological Survey and Utah Energy and Geoscience Institute. Salt Lake City, Utah.

ARI (1990 through 2011) *CO_2 Use in Enhanced Oil Recovery.* Deliverable to ICF International under Task Order 102, July 15, 2011.

ARI (2007) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, DC. April 20-21, 2007.

ARI (2006) *CO_2-EOR: An Enabling Bridge for the Oil Transition*. Presented at "Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions." Washington, DC. April 20-21, 2006.

Broadhead (2003) Personal communication. Ron Broadhead, Principal Senior Petroleum Geologist and Adjunct faculty, Earth and Environmental Sciences Department, New Mexico Bureau of Geology and Mineral Resources, and Robin Pestrusak, ICF International. September 5, 2003.

COGCC (2011) Monthly Production Reports. Available online at < http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyCO2ProdByCounty>. Accessed September 2011.

Denbury Resources Inc. (2002 through 2011) *Annual Report: Form 10-K.* Available online at <http://ir.denbury.com/phoenix.zhtml?c=72374&p=irol-reportsAnnual>. Accessed September 2011.

New Mexico Bureau of Geology and Mineral Resources (2006) Natural Accumulations of Carbon Dioxide in New Mexico and Adjacent Parts of Colorado and Arizona: Commercial Accumulation of CO_2. Available online at <http://geoinfo.nmt.edu/staff/broadhead/CO_2.html#commercial>.

Phosphoric Acid Production

EFMA (2000) "Production of Phosphoric Acid." *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry.* Booklet 4 of 8. European Fertilizer Manufacturers Association. Available online at <http://www.efma.org/Publications/BAT%202000/Bat04/section04.asp>.

FIPR (2003) "Analyses of Some Phosphate Rocks." Facsimile Gary Albarelli, the Florida Institute of Phosphate Research, Bartow, Florida, to Robert Lanza, ICF International. July 29, 2003.

FIPR (2003a) Florida Institute of Phosphate Research. Personal communication. Mr. Michael Lloyd, Laboratory Manager, FIPR, Bartow, Florida, to Mr. Robert Lanza, ICF International. August 2003.

USGS (1994 through 2011) *Minerals Yearbook*. *Phosphate Rock Annual Report*. U.S. Geological Survey, Reston, VA.

Iron and Steel Production and Metallurgical Coke Production

AISI (2004 through 2011a) *Annual Statistical Report*, American Iron and Steel Institute, Washington, DC.

AISI (2011b) Personal communication, Paul Stewart, ICF International, and the American Iron and Steel Institute, August, 2011.

AISI (2008b) Personal communication, Mausami Desai, US EPA, and the American Iron and Steel Institute, October 2008.

DOE (2000) *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. Office of Industrial Technologies, U.S. Department of Energy. August 2000. DOE/EE-0229.EIA

EIA (2011a) *Annual Energy Review 2010,* Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0384(2010).

EIA (2011b) *Natural Gas Annual 2010,* Energy Information Administration, U.S. Department of Energy.

Washington, DC. DOE/EIA-0131(10).

EIA (2011c) Supplemental Tables on Petroleum Product detail. Monthly Energy Review, September 2011, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2011/09).

EIA (1998 through 2011d) *Quarterly Coal Report: October-December*, Energy Information Administration, U.S. Department of Energy. Washington, DC. DOE/EIA-0121.

EIA (1992) Coal and lignite production. *EIA State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1995) “Volume 3: Greenhouse Gas Inventory Reference Manual. Table 2-2”.*IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. IPCC WG1 Technical Support Unit, United Kingdom.

USGS (2011) *Mineral Industry Surveys: Iron and Steel Scrap in December 2010.* U.S. Geological Survey, Reston, VA.

Ferroalloy Production

Corathers, L. (2011) Personal communication. Lisa Corathers, Commodity Specialist, U.S. Geological Survey and Paul Stewart, ICF International. March 11, 2011.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Onder, H., and E.A. Bagdoyan (1993) Everything You’ve Always Wanted to Know about Petroleum Coke. Allis Mineral Systems.

USGS (1991 through 2010) Minerals Yearbook: Silicon Annual Report. U.S. Geological Survey, Reston, VA.

Aluminum Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. Montreal. May 2000. IPCC-XVI/Doc. 10 (1.IV.2000).

USAA (2004, 2005, 2006) *Primary Aluminum Statistics.* U.S. Aluminum Association, Washington, DC.

USAA (2008, 2009) *U.S. Primary Aluminum Production.* U.S. Aluminum Association, Washington, DC.

USAA (2010) *U.S. Primary Aluminum Production.* U.S. Aluminum Association, Washington, DC.

USGS (1995, 1998, 2000, 2001, 2002) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2007) *2006 Mineral Yearbook: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2009a) *2008 Mineral Yearbook: Aluminum.* U.S. Geological Survey, Reston, VA.

USGS (2009b) *Mineral Industry Surveys: Aluminum in December 2008*. U.S. Geological Survey, Reston, VA.

USGS (2010a) *2009 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2010b) *Mineral Industry Surveys: Aluminum in December 2009*. U.S. Geological Survey, Reston, VA.

USGS (2010c) *Mineral Industry Surveys: Aluminum in September 2010*. U.S. Geological Survey, Reston, VA.

Magnesium Production and Processing

Bartos S., C. Laush, J. Scharfenberg, and R. Kantamaneni (2007) "Reducing greenhouse gas emissions from magnesium die casting," *Journal of Cleaner Production*, 15: 979-987, March.

Gjestland, H. and D. Magers (1996) "Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry," #13, *1996 Annual Conference Proceedings*, International Magnesium Association. Ube City, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

RAND (2002) RAND Environmental Science and Policy Center, "Production and Distribution of SF_6 by End-Use Applications" Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. San Diego, CA. November 21-22, 2002.

USGS (2002, 2003, 2005 through 2008, and 2010b) Minerals Yearbook: Magnesium Annual Report. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>.

USGS (2010a) *Mineral Commodity Summaries: Magnesium Metal*. U.S. Geological Survey, Reston, VA. Available online at < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2010-mgmet.pdf>.

Zinc Production

Horsehead Corp. (2011). 10-k Annual Report for the Fiscal Year Ended December, 31 2010. Available at: <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted March 16, 2011.

Horsehead Corp. (2010a). 10-k Annual Report for the Fiscal Year Ended December, 31 2009. Available at: <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted March 16, 2010.

Horsehead Corp. (2010b). *Horsehead Holding Corp. Provides Update on Operations at its Monaca, PA Plant.* July 28, 2010. Available at: <http://www.horsehead.net/pressreleases.php?showall=no&news=&ID=65>.

Horsehead Corp (2008). 10-k Annual Report for the Fiscal Year Ended December, 31 2007. Available at: <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted March 31, 2008.

Horsehead Corp (2007). Registration Statement (General Form) S-1. Available at <http://google.brand.edgar-online.com/default.aspx?sym=zinc>. Submitted April 13, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

PIZO (2011). Available at <http://pizotech.com/index.html>. Accessed November 17, 2010.

Sjardin (2003) CO_2 *Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Steel Dust Recycling LLC (2010). Available at < http://steeldust.com/home.htm>. Accessed November 17, 2011.

USGS (2011a). *2011 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA.

USGS (1994 through 2011b) *Minerals Yearbook: Zinc Annual Report.* U.S. Geological Survey, Reston, VA.

Viklund-White C. (2000) "The Use of LCA for the Environmental Evaluation of the Recycling of Galvanized Steel." ISIJ International. Volume 40 No. 3: 292-299.

Lead Production

Dutrizac, J.E., V. Ramachandran, and J.A. Gonzalez (2000) *Lead-Zinc 2000*. The Minerals, Metals, and Materials Society.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Morris, D., F.R. Steward, and P. Evans (1983) *Energy Efficiency of a Lead Smelter.* Energy 8(5):337-349.

Sjardin, M. (2003) *CO_2 Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Ullman (1997). *Ullman's Encyclopedia of Industrial Chemistry: Fifth Edition.* Volume A5. John Wiley and Sons.

USGS (2011a) Personal Communication between David Guberman of USGS and Paul Stewart of ICF International, August 31, 2011.

USGS (2011b) *2011 Mineral Commodity Summary, Lead.* U.S. Geological Survey, Reston, VA.

USGS (1994 through 2011c) *Minerals Yearbook: Lead Annual Report.* U.S. Geological Survey, Reston, VA.

HCFC-22 Production

ARAP (2010) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 10, 2010.

ARAP (2009) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 21, 2009.

ARAP (2008) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 17, 2008.

ARAP (2007) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 2, 2007.

ARAP (2006) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. July 11, 2006.

ARAP (2005) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 9, 2005.

ARAP (2004) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. June 3, 2004.

ARAP (2003) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 18, 2003.

ARAP (2002) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 7, 2002.

ARAP (2001) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 6, 2001.

ARAP (2000) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 13, 2000.

ARAP (1999) Facsimile from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger Schaefer of the U.S. Environmental Protection Agency. September 23, 1999.

ARAP (1997) Letter from Dave Stirpe, Director, Alliance for Responsible Atmospheric Policy to Elizabeth Dutrow of the U.S. Environmental Protection Agency. December 23, 1997.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

RTI (1997) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22: Emissions from 1990 through 1996." Report prepared by Research Triangle Institute for the Cadmus Group. November 25, 1997; revised February 16, 1998.

RTI (2008) "Verification of Emission Estimates of HFC-23 from the Production of HCFC-22:Emissions from 1990 through 2006." Report prepared by RTI International for the Climate Change Division. March, 2008.

Substitution of Ozone Depleting Substances

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Semiconductor Manufacture

Burton, C.S., and R. Beizaie (2001) "EPA's PFC Emissions Model (PEVM) v. 2.14: Description and Documentation" prepared for Office of Global Programs, U. S. Environmental Protection Agency, Washington, DC. November 2001.

Citigroup Smith Barney (2005) *Global Supply/Demand Model for Semiconductor*s. March 2005.

ITRS (2007, 2008) *International Technology Roadmap for Semiconductors: 2006 Update*. January 2007; *International Technology Roadmap for Semiconductors: 2007 Edition, January 2008;* Available online at <http://www.itrs.net/Links/2007ITRS/Home2007.htm>. Theses and earlier editions and updates are available at <http://public.itrs.net>. Information about the number of interconnect layers for years 1990–2010 is contained in Burton and Beizaie, 2001. PEVM is updated using new editions and updates of the ITRS, which are published annually.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, eds. Institute for Global Environmental Strategies (IGES). Hayama, Kanagawa, Japan.

Semiconductor Equipment and Materials Industry (2010) *World Fab Forecast*, *November 2010 Edition*.

Semiconductor Industry Association (SIA) (2009). STATS: SICAS Capacity and Utilization Rates Q1-Q4 2008, Q1-Q4 2009. Available online at <http://www.sia-online.org/cs/papers_publications/statistics>.

U.S. EPA (2006) *Uses and Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector.* U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-06-901.

VLSI Research, Inc. (2010). Worldwide Silicon Demand by Wafer Size, by Linewidth and by Device Type, v. 9.09. August 2010.

Electrical Transmission and Distribution

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

O'Connell, P., F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, J.P. Tailebois (2002) *SF_6 in the Electric Industry, Status 2000,* CIGRE. February 2002.

RAND (2004) "Trends in SF_6 Sales and End-Use Applications: 1961-2003," Katie D. Smythe. *International Conference on SF_6 and the Environment: Emission Reduction Strategies*. RAND Environmental Science and Policy Center, Scottsdale, AZ. December 1-3, 2004.

UDI (2010) *2010 UDI Directory of Electric Power Producers and Distributors, 118th Edition*, Platts.

UDI (2007) *2007 UDI Directory of Electric Power Producers and Distributors, 115th Edition*, Platts.

UDI (2004) *2004 UDI Directory of Electric Power Producers and Distributors, 112th Edition*, Platts.

UDI (2001) *2001 UDI Directory of Electric Power Producers and Distributors, 109th Edition*, Platts.

Industrial Sources of Indirect Greenhouse Gases

EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

EPA (2009). "1970 - 2008 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions*

Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards. Available

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

Solvent and Other Product Use

Nitrous Oxide from Product Uses

Airgas (2007) Airgas, INC. Form 10-K. Annual Report Pursuant to Section 13 or 15 (d) of the SEC Act of 1934. Fiscal year ended March, 31, 2007. Available online at <http://www.sec.gov/Archives/edgar/data/804212/000089322007002057/w35445e10vk.htm#102>

CGA (2003) "CGA Nitrous Oxide Abuse Hotline: CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. November 3, 2003.

CGA (2002) "CGA/NWSA Nitrous Oxide Fact Sheet." Compressed Gas Association. March 25, 2002.

FTC (2001) Federal Trade Commission: *Analysis of Agreement Containing Consent Order To Aid Public Comment.* FTC File No. 001-0040. October, 2001. Available online at <http://www.ftc.gov/os/2001/10/airgasanalysis.htm >

Heydorn, B. (1997) "Nitrous Oxide—North America." *Chemical Economics Handbook*, SRI Consulting. May 1997.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Tupman, M. (2003) Personal communication .Martin Tupman, Airgas Nitrous Oxide and Daniel Lieberman, ICF International. August 8, 2003.

Tupman, M. (2002) Personal communication. Martin Tupman of Airgas Nitrous Oxide and Laxmi Palreddy, ICF International. July 3, 2002.

Solvent Use

EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

EPA (2009). "1970 - 2008 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

Agriculture

Enteric Fermentation

Archibeque, S. (2011). Personal Communication. Shawn Archibeque, Colorado State University, Fort Collins, Colorado and staff at ICF International.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986) Methane Production by Domestic Animals, Wild Ruminants, Other Herbivores, Fauna, and Humans. *Tellus*, 38B:271-284.

Donovan, K. (1999) Personal Communication. Kacey Donovan, University of California at Davis and staff at ICF International.

Doren, P.E., J. F. Baker, C. R. Long and T. C. Cartwright (1989) Estimating Parameters of Growth Curves of Bulls, *J Animal Science* 67:1432-1445.

Enns, M. (2008) Personal Communication. Dr. Mark Enns, Colorado State University and staff at ICF International.

FAO (2011) *FAOSTAT Statistical Database*. Food and Agriculture Organization of the United Nations. Available online at <http://apps.fao.org>.

Galyean and Gleghorn (2001) Summary of the 2000 Texas Tech University Consulting Nutritionist Survey. Texas Tech University. Available online at <http://www.depts.ttu.edu/afs/burnett_center/progress_reports/bc12.pdf>. June 2009.

Holstein Association (2010) *History of the Holstein Breed* (website). Available online at <http://www.holsteinusa.com/holstein_breed/breedhistory.html>. Accessed September 2010.

ICF (2006) *Cattle Enteric Fermentation Model: Model Documentation*. Prepared by ICF International for the Environmental Protection Agency. June 2006.

ICF (2003) *Uncertainty Analysis of 2001 Inventory Estimates of Methane Emissions from Livestock Enteric Fermentation in the U.S*. Memorandum from ICF International to the Environmental Protection Agency. May 2003.

IPCC (2006) 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2000*) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. Montreal. May 2000. IPCC-XVI/Doc. 10 (1.IV.2000).

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Johnson, D. (2002) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and ICF International.

Johnson, D. (1999) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and David Conneely, ICF International.

Johnson, K. (2010) Personal Communication. Kris Johnson, Washington State University, Pullman, and ICF International.

Kebreab E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. *J. Anim. Sci.* 86: 2738-2748.

Lippke, H., T. D. Forbes, and W. C. Ellis. (2000) Effect of supplements on growth and forage intake by stocker steers grazing wheat pasture. *J. Anim. Sci.* 78:1625-1635

National Bison Association (2011) Handling & Carcass Info (on website). Available online at: <http://www.bisoncentral.com/about-bison/handling-and-carcass-info>. Accessed August 16, 2011.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.

NRC (1999) *1996 Beef NRC: Appendix Table 22*. National Research Council.

NRC (1984) *Nutrient requirements for beef cattle (6th Ed.)*. National Academy Press, Washington, DC.

Pinchak, W.E., D. R. Tolleson, M. McCloy, L. J. Hunt, R. J. Gill, R. J. Ansley, and S. J. Bevers (2004) Morbidity effects on productivity and profitability of stocker cattle grazing in the southern plains. J. Anim. Sci. 82:2773-2779.

Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith (2003) Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. J. Anim. Sci. 81:984-996.

Skogerboe, T. L., L. Thompson, J. M. Cunningham, A. C. Brake, V. K. Karle (2000) The effectiveness of a single dose of doramectin pour-on in the control of gastrointestinal nematodes in yearling stocker cattle. Vet. Parasitology

87:173-181.

USDA (2011) *Quick Stats: Agricultural Statistics Database*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://quickstats.nass.usda.gov/>. Accessed June 28, 2011.

USDA (2010) Beef 2007–08, Part *V: Reference of Beef Cow-calf Management Practices in the United States, 2007–08*. USDA–APHIS–VS, CEAH. Fort Collins, CO #532.0410.

USDA (1997) *Census of Agriculture: 1997 Census Report*. United States Department of Agriculture. Available online at: <http://www.agcensus.usda.gov/Publications/1997/index.asp>. Accessed July 18, 2011.

USDA (1996) *Beef Cow/Calf Health and Productivity Audit (CHAPA): Forage Analyses from Cow/Calf Herds in 18 States*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>. March 1996.

USDA (1992) Census *of Agriculture: 1992 Census Report*. United States Department of Agriculture. Available online at: <http://www.agcensus.usda.gov/Publications/1992/index.asp>. Accessed July 18, 2011.

USDA:APHIS:VS (2002) *Reference of 2002 Dairy Management Practices*. National Animal Health Monitoring System. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1998) *Beef '97*. National Animal Health Monitoring System. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1996) *Reference of 1996 Dairy Management Practices*. National Animal Health Monitoring System. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1994) *Beef Cow/Calf Health and Productivity Audit*. National Animal Health Monitoring System. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

USDA:APHIS:VS (1993) *Beef Cow/Calf Health and Productivity Audit*. National Animal Health Monitoring System. Fort Collins, CO. August 1993. Available online at <http://www.aphis.usda.gov/vs/ceah/cahm>.

Vasconcelos and Galyean (2007) Nutritional recommendations of feedlot consulting nutritionists: The 2007 Texas Tech University Study. J. Anim. Sci. 85:2772-2781.

Manure Management

Anderson, S. (2000) Personal Communication. Steve Anderson, Agricultural Statistician, National Agriculture Statistics Service, U.S. Department of Agriculture and Lee-Ann Tracy, ERG. Washington, DC. May 31, 2000.

ASAE (1998) *ASAE Standards 1998, 45th Edition*. American Society of Agricultural Engineers. St. Joseph, MI.

Bryant, M.P., V.H. Varel, R.A. Frobish, and H.R. Isaacson (1976) In H.G. Schlegel (ed.); *Seminar on Microbial Energy Conversion*. E. Goltz KG. Göttingen, Germany.

Deal, P. (2000) Personal Communication. Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 21, 2000.

EPA (2011). AgSTAR Anaerobic Digester Database. Available online at: <http://www.epa.gov/agstar/projects/index.html#database>.

EPA (2008) *Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type Managing Manure with Biogas Recovery Systems*. Available online at <http://www.epa.gov/climateleaders/documents/resources/ClimateLeaders_DraftManureOffsetProtocol.pdf>.

EPA (2006) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, DC. Winter 2006. Available online at <http://www.epa.gov/agstar/pdf/2006digest.pdf>. Retrieved July 2006.

EPA (2005) *National Emission Inventory—Ammonia Emissions from Animal Agricultural Operations, Revised Draft Report*. U.S. Environmental Protection Agency. Washington, DC. April 22, 2005. Available online at <ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/nonpoint/nh3inventory_draft_042205.pdf>. Retrieved August 2007.

EPA (2003) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, DC.

Winter 2003. Available online at <http://www.epa.gov/agstar/pdf/2003digest.pdf>. Retrieved July 2006.

EPA (2002a) *Development Document for the Final Revisions to the National Pollutant Discharge Elimination System (NPDES) Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (CAFOS).* U.S. Environmental Protection Agency. EPA-821-R-03-001. December 2002.

EPA (2002b) *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations*. U.S. Environmental Protection Agency. EPA-821-R-03-004. December 2002.

EPA (2000) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, DC. Spring 2000. Available online at: http://www.epa.gov/agstar/news-events/digest/2000digest.pdf .

EPA (1992) *Global Methane Emissions from Livestock and Poultry Manure*, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

ERG (2010a) "Typical Animal Mass Values for Inventory Swine Categories." Memorandum to EPA from ERG. July 19, 2010.

ERG (2010b) Telecon with William Boyd of USDA NRCS and Cortney Itle of ERG Concerning Updated VS and Nex Rates. August 8, 2010.

ERG (2010c) "Updating Current Inventory Manure Characteristics new USDA Agricultural Waste Management Field Handbook Values." Memorandum to EPA from ERG. August 13, 2010.

ERG (2008) "Methodology for Improving Methane Emissions Estimates and Emission Reductions from Anaerobic Digestion System for the 1990-2007 Greenhouse Gas Inventory for Manure Management." Memorandum to EPA from ERG. August 18, 2008.

ERG (2003) "Methodology for Estimating Uncertainty for Manure Management Greenhouse Gas Inventory." Contract No. GS-10F-0036, Task Order 005. Memorandum to EPA from ERG, Lexington, MA. September 26, 2003.

ERG (2001) *Summary of development of MDP Factor for methane conversion factor calculations.* ERG, Lexington, MA. September 2001.

ERG (2000a) *Calculations: Percent Distribution of Manure for Waste Management Systems.* ERG, Lexington, MA. August 2000.

ERG (2000b) *Discussion of Methodology for Estimating Animal Waste Characteristics* (Summary of B_o Literature Review). ERG, Lexington, MA. June 2000.

FAO (2011) *Yearly U.S. total horse population data from the Food and Agriculture Organization of the United Nations database*. Available online at <http://faostat.fao.org>. August 2011.

Garrett, W.N. and D.E. Johnson (1983) "Nutritional energetics of ruminants." *Journal of Animal Science*, 57(suppl.2):478-497.

Groffman, P.M., R. Brumme, K. Butterbach-Bahl, K.E. Dobbie, A.R. Mosier, D. Ojima, H. Papen, W.J. Parton, K.A. Smith, and C. Wagner-Riddle (2000) "Evaluating annual nitrous oxide fluxes at the ecosystem scale." *Global Biogeochemcial Cycles,* 14(4):1061-1070.

Hashimoto, A.G. (1984) "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." *Agricultural Wastes*, 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen (1981) "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." *Agricultural Wastes*, 3:241-256.

Hill, D.T. (1984) "Methane Productivity of the Major Animal Types." *Transactions of the ASAE*, 27(2):530-540.

Hill, D.T. (1982) "Design of Digestion Systems for Maximum Methane Production." *Transactions of the ASAE*, 25(1):226-230.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T.

Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Johnson, D. (2000) Personal Communication. Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 23, 2000.

Lange, J. (2000) Personal Communication. John Lange, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service and Lee-Ann Tracy, ERG. Washington, DC. May 8, 2000.

Miller, P. (2000) Personal Communication. Paul Miller, Iowa Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 12, 2000.

Milton, B. (2000) Personal Communication. Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service and Lee-Ann Tracy, ERG. May 1, 2000.

Moffroid , K and D. Pape. (2011) *1990-2009 Volatile Solids and Nitrogen Excretion Rates*. Dataset to EPA from ICF International. June 2011.

Morris, G.R. (1976) *Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation.* M.S. Thesis. Cornell University.

NOAA (2011) *National Climate Data Center (NCDC).* Available online at <ftp://ftp.ncdc.noaa.gov/pub/data/cirs/> (for all states except Alaska and Hawaii) and <ftp://ftp.ncdc.noaa.gov/pub/data/gsod/2008/> (for Alaska and Hawaii). June 2011.

Pederson, L., D. Pape and K. Moffroid (2007) *1990-2006 Volatile Solids and Nitrogen Excretion Rates*, EPA Contract GS-10F-0124J, Task Order 056-01. Memorandum to EPA from ICF International. August 2007.

Safley, L.M., Jr. and P.W. Westerman (1990) “Psychrophilic anaerobic digestion of animal manure: proposed design methodology.” *Biological Wastes*, 34:133-148.

Safley, L.M., Jr. (2000) Personal Communication. Deb Bartram, ERG and L.M. Safley, President, Agri-Waste Technology. June and October 2000.

Stettler, D. (2000) Personal Communication. Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 27, 2000.

Sweeten, J. (2000) Personal Communication. John Sweeten, Texas A&M University and Indra Mitra, ERG. June 2000.

UEP (1999) *Voluntary Survey Results—Estimated Percentage Participation/Activity*, Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

USDA (2011a) *Quick Stats 1.0*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at < http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/index.asp >

USDA (2011b) *Chicken and Eggs 2010 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. February 2011. Available online at <http://www.nass.usda.gov/Publications/index.asp> .

USDA (2011c) *Poultry - Production and Value 2010 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. April 2011. Available online at <http://usda.mannlib.cornell.edu/usda/nass/PoulProdVa//2010s/2011/PoulProdVa-04-28-2011_new_format.pdf> .

USDA (2009a) *1992, 1997, 2002, and 2007 Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://www.nass.usda.gov/census/>. December 2009.

USDA (2009b) *Chicken and Eggs 2008 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. February 2009. Available online at <http://www.nass.usda.gov/Publications/index.asp> .

USDA (2009c) *Poultry - Production and Value 2008 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. April 2009. Available online at <http://www.nass.usda.gov/Publications/index.asp> .

USDA (2009d) *Chicken and Eggs – Final Estimates 2003-2007*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. March 2009. Available online at <http://usda.mannlib.cornell.edu/usda/nass/SB980/sb1024.pdf> .

USDA (2009e) *Poultry Production and Value—Final Estimates 2003-2007*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. May 2009. Available online at < http://usda.mannlib.cornell.edu/usda/nass/SB994/sb1028.pdf>

USDA (2008) *Agricultural Waste Management Field Handbook*, *National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture.

USDA (2004a) *Chicken and Eggs—Final Estimates 1998-2003*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. April 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004b) *Poultry Production and Value—Final Estimates 1998-2002*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. April 2004. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2003) *APHIS Sheep 2001,Parts I and IV*. Available online at <http://www.aphis.usda.gov/vs/ceah/ncahs/nahms/sheep/>.

USDA (2000a) *National Animal Health Monitoring Systems (NAHMS) Dairy '96 Study.* Stephen L. Ott, Animal and Plant Health Inspection Service, U.S. Department of Agriculture. June 19, 2000.

USDA (2000b) *Layers '99—Part II: References of 1999 Table Egg Layer Management in the U.S.* Animal and Plant Health Inspection Service (APHIS), National Animal Health Monitoring System (NAHMS), U.S. Department of Agriculture. January 2000.

USDA (1999) *Poultry Production and Value—Final Estimates 1994-97*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. March 1999. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1998a) *Chicken and Eggs—Final Estimates 1994-97*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. December 1998. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1998b) *National Animal Health Monitoring System's (NAHMS) Swine '95 Study.* Eric Bush, Centers for Epidemiology and Animal Health , U.S. Department of Agriculture.

USDA (1996a) *Agricultural Waste Management Field Handbook*, *National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1996b) *Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices.* Animal Plant Health and Inspection Service, U.S. Department of Agriculture. Washington, DC. June 1996.

USDA (1995a) *Poultry Production and Value—Final Estimates 1988-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. March 1995. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1995b) *Chicken and Eggs—Final Estimates 1988-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. December 1995. Available online at <http://usda.mannlib.cornell.edu/reports/general/sb/>.

Rice Cultivation

Anderson, M. (2008 through 2011). Email correspondence. Monte Anderson, Oklahoma Farm Service Agency and ICF International.

Beighley, D. (2011). Email correspondence. Donn Beighley, Southeast Missouri State University, Department of Agriculture and ICF International.

Bollich, P. (2000) Personal Communication. Pat Bollich, Professor with Louisiana State University Agriculture

Center and Payton Deeks, ICF International.

Bossio, D.A., W. Horwath, R.G. Mutters, and C. van Kessel (1999) "Methane pool and flux dynamics in a rice field following straw incorporation." *Soil Biology and Biochemistry,* 31:1313-1322.

Buehring, N. (2009 through 2011) Email correspondence. Nathan Buehring, Assistant Professor and Extension Rice Specialist, Mississippi State University Delta Branch Exp. Station and ICF International.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Cicerone R.J., C.C. Delwiche, S.C. Tyler, and P.R. Zimmerman (1992) "Methane Emissions from California Rice Paddies with Varied Treatments." *Global Biogeochemical Cycles,* 6:233-248.

Deren, C. (2002) Personal Communication and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

Fife, L. (2011) Email correspondence. Les Fife, Sacramento Valley AgBurn Coordinator and ICF International.

Gonzalez, R. (2007 through 2011) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Guethle, D. (1999 through 2010) Personal Communication. David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service and ICF International.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler (1985) "Production, Oxidation, and Emissions of Methane in Rice Paddies." *FEMS Microbiology Ecology,* 31:343-351.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change, Montreal. May 2000. IPCC-XVI/Doc. 10 (1.IV.2000).

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Kirstein, A. (2003 through 2004, 2006) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL and ICF International.

Klosterboer, A. (1997, 1999 through 2003) Personal Communication. Arlen Klosterboer, retired Extension Agronomist, Texas A&M University and ICF International. July 7, 2003.

Lancero, J. (2006 through 2010) Email correspondence. Jeff Lancero, California Air Resources Board and ICF International.

Lee, D. (2003 through 2007) Email correspondence. Danny Lee, OK Farm Service Agency and ICF International.

Lindau, C.W. and P.K. Bollich (1993) "Methane Emissions from Louisiana First and Ratoon Crop Rice." *Soil Science,* 156:42-48.

Lindau, C.W., P.K Bollich, and R.D. DeLaune (1995) "Effect of Rice Variety on Methane Emission from Louisiana Rice." *Agriculture, Ecosystems and Environment,* 54:109-114.

Linscombe, S. (1999, 2001 through 2011) Email correspondence. Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center and ICF International.

Mayhew, W. (1997) Personal Communication. Walter Mayhew, University of Arkansas, Little Rock and Holly Simpkins, ICF Incorporated. November 24, 1997.

Mutters, C. (2001 through 2005) Personal Communication. Mr. Cass Mutters, Rice Farm Advisor for Butte, Glen, and Tehama Counties University of California, Cooperative Extension Service and ICF International.

Sacramento Valley Basinwide Air Pollution Control Council (2005, 2007) *Report on the Conditional Rice Straw Burning Permit Program*. Available online at <http://www.bcaqmd.org/default.asp?docpage=html/bcc.htm>.

Saichuk, J. (1997) Personal Communication. John Saichuk, Louisiana State University and Holly Simpkins, ICF Incorporated. November 24, 1997.

Sass, R.L., F.M Fisher, P.A. Harcombe, and F.T. Turner (1991a) "Mitigation of Methane Emissions from Rice Fields: Possible Adverse Effects of Incorporated Rice Straw." *Global Biogeochemical Cycles,* 5:275-287.

Sass, R.L., F.M. Fisher, F.T. Turner, and M.F. Jund (1991b) "Methane Emissions from Rice Fields as Influenced by Solar Radiation, Temperature, and Straw Incorporation." *Global Biogeochemical Cycles,* 5:335-350.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner (1990) "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles,* 4:47-68.

Schueneman, T. (1997, 1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International.

Slaton, N. (1999 through 2001) Personal Communication. Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service and ICF International.

Stansel, J. (2004 through 2005) Email correspondence. Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center and ICF International.

Stevens, G. (1997) Personal Communication. Gene Stevens, Extension Specialist, Missouri Commercial Agriculture Program, Delta Research Center and Holly Simpkins, ICF Incorporated. December 17, 1997.

Street, J. (1997, 1999 through 2003) Personal Communication. Joe Street, Rice Specialist, Mississippi State University, Delta Research Center and ICF International.

Texas Agricultural Experiment Station (2007 through 2011) *Texas Rice Acreage by Variety*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System. Available online at <http://beaumont.tamu.edu/CropSurvey/CropSurveyReport.aspx>.

Texas Agricultural Experiment Station (2006) *2005 - Texas Rice Crop Statistics Report*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System, p. 8. Available online at <http://beaumont.tamu.edu/eLibrary/TRRFReport_default.htm>.

USDA (2005 through 2011) *Crop Production Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>.

USDA (2003) *Field Crops, Final Estimates 1997-2002*. Statistical Bulletin No. 982. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/usda/reports/general/sb/>. September 2005.

USDA (1998) *Field Crops Final Estimates 1992-1997*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/>. July 2001.

USDA (1994) *Field Crops Final Estimates 1987-1992*. Statistical Bulletin Number 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/>. July 2001.

Walker, T. (2005, 2007 through 2008) Email correspondence. Tim Walker, Assistant Research Professor, Mississippi State University Delta Branch Exp. Station and ICF International.

Wilson, C. (2002 through 2007, 2009 through 2011) Personal Communication. Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service and ICF International.

Agricultural Soil Management

AAPFCO (1995 through 2000b, 2002 through 2009) *Commercial Fertilizers*. Association of American Plant Food Control Officials. University of Kentucky, Lexington, KY.

AAPFCO (2000a) 1999-2000 Commercial Fertilizers Data, ASCII files. Available from David Terry, Secretary, Association of American Plant Food Control Officials.

Alexander, R.B. and R.A. Smith (1990) *County-Level Estimates of Nitrogen and Phosphorous Fertilizer Use in the United States, 1945-1985*. U.S. Geological Survey Open File Report 90-130.

Anonymous (1924) Fertilizer Used on Cotton, 1923-1924. "Miscellaneous Agricultural Statistics," Table 753. *1924 Yearbook of the Department of Agriculture,* 1171.

Bastian, R. (2007) Personal Communication. Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC and Victoria Thompson, ICF International. July 20, 2007.

Battaglin, W.A., and D.A. Goolsby (1994) *Spatial Data in Geographic Information System Format on Agricultural Chemical Use, Land Use, and Cropping Practices in the United States*. U.S. Geological Survey Water-Resources Investigations Report 94-4176.

Bogue A.G. (1963) *From Prairie to Corn Belt: Farming on the Illinois and Iowa prairies in the Nineteenth Century*. The University of Chicago Press. Chicago, IL.

Bonnen C.A., and F.F. Elliott (1931) *Type of Farming Areas in Texas*. Bulletin Number 427, Texas Agricultural Experiment Station, Agricultural and Mechanical College of Texas.

Brenner, J., K. Paustian, G. Bluhm, J. Cipra, M. Easter, R. Foulk, K. Killian, R. Moore, J. Schuler, P. Smith, and S. Williams (2002) *Quantifying the Change in Greenhouse Gas Emissions Due to Natural Resource Conservation Practice Application in Nebraska*. Colorado State University Natural Resource Ecology Laboratory and Natural Resources Conservation Service, U.S. Department of Agriculture. Fort Collins, CO.

Brenner, J., K. Paustian., G. Bluhm, J. Cipra, M. Easter, E.T. Elliott, T. Koutza, K. Killian, J. Schuler, S. Williams (2001) *Quantifying the Change in Greenhouse Gas Emissions Due to Natural Resource Conservation Practice Application in Iowa*. Final report to the Iowa Conservation Partnership. Colorado State University Natural Resource Ecology Laboratory and U.S. Department of Agriculture Natural Resources Conservation Service. Fort Collins, CO.

Chilcott E.C. (1910) *A Study of Cultivation Methods and Crop Rotations for the Great Plains Area*. Bureau of Plant Industry Bulletin Number 187, U.S. Department of Agriculture. Government Printing Office. Washington, DC.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

Cochran, W.G. (1977) *Sampling Techniques, Third Edition*. Wiley Publishing, New York.

CTIC (1998) *1998 Crop Residue Management Executive Summary*. Conservation Technology Information Center. Available online at <http://www.ctic.purdue.edu/Core4/CT/CT.html>.

Daly, C., G.H. Taylor, W.P. Gibson, T. Parzybok, G.L. Johnson, and P.A. Pasteris (1998) "Development of high-quality spatial datasets for the United States." *Proc., 1st International Conference on Geospatial Information in Agriculture and Forestry*, Lake Buena Vista, FL, I-512-I-519. June 1-3, 1998.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) "A statistical-topographic model for mapping climatological precipitation over mountainous terrain." *Journal of Applied Meteorology*, 33:140-158.

David, M.B., S.J. Del Grosso, X. Hu, G.F. McIsaac, W.J. Parton, E.P. Marshall, C. Tonitto, and M.A. Youssef (2009) "Modeling denitrification in a tile-drained, corn and soybean agroecosystem of Illinois, USA." *Biogeochemistry* 93:7-30.

DAYMET (No date) *Daily Surface Weather and Climatological Summaries*. Numerical Terradynamic Simulation Group (NTSG), University of Montana. Available online at <http://www.daymet.org>.

Delgado, J.A., S.J. Del Grosso, and S.M. Ogle (2009) "15N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated." *Nutrient Cycling in Agroecosystems*, DOI 10.1007/s10705-009-9300-9.

Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DayCent modeling package and additional procedures for parameterization, calibration, validation, and applications, in *Methods of*

Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from US Cropland Soils." *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544.

Del Grosso, S.J., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating agricultural nitrous oxide emissions. *EOS 89*, 529-530.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research*, 83: 9-24. doi: 10.1016/j.still.2005.02.007.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.)*; Modeling Carbon and Nitrogen Dynamics for Soil Management*. CRC Press. Boca Raton, Florida. 303-332.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, D.S. Ojima, A.E. Kulmala and S. Phongpan (2000) General model for N_2O and N_2 gas emissions from soils due to denitrification. *Global Biogeochem. Cycles*, 14:1045-1060.

Edmonds, L., N. Gollehon, R.L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaeffer (2003) "Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans." Part 1. *Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping*. Natural Resource Conservation Service, U.S. Department of Agriculture.

Elliott, F.F. (1933) *Types of Farming in the United States*. U.S. Department of Commerce. Government Printing Office. Washington, DC.

Elliott, F.F. and J.W. Tapp (1928) *Types of Farming in North Dakota*. U.S. Department of Agriculture Technical Bulletin Number 102.

Ellsworth, J.O. (1929) *Types of Farming in Oklahoma*. Agricultural Experiment Station Bulletin Number 181. Oklahoma Agricultural and Mechanical College.

Engle, R.H. and B.R. Makela (1947) "Where is All the Fertilizer Going?" The National Fertilizer Association. *The Fertilizer Review*, Vol. XXII, 6:7-10.

EPA (2003) *Clean Watersheds Needs Survey 2000—Report to Congress*, U.S. Environmental Protection Agency. Washington, DC. Available online at <http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm>.

EPA (1999) *Biosolids Generation, Use and Disposal in the United States*. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at <http://biosolids.policy.net/relatives/18941.PDF>.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403, and 503.

ERS (2003) *Ag Chemical and Production Technology*. Economic Research Service, U.S. Department of Agriculture.

ERS (2002) Economic Research Service, U.S. Department of Agriculture. Available online at <http://www.ers.usda.gov/>.

ERS (1994) *Fertilizer Use and Price Statistics*. Stock #86012. Economic Research Service, U.S. Department of Agriculture.

ERS (1988) *Agricultural Resources—Inputs Situation and Outlook Report*. AR-9. Economic Research Service, U.S. Department of Agriculture.

Fraps, G.S. and S.E. Asbury (1931) *Commercial Fertilizers in 1930-1931 and Their Uses*. Agricultural Experiment Station Bulletin Number 434. Agricultural and Mechanical College of Texas.

Hardies, E.W. and A.N. Hume (1927) *Wheat in South Dakota*. Agronomy Department Bulletin Number 222. Agricultural Experiment Station, South Dakota State College of Agriculture and Mechanical Arts. Brookings, SD.

Garey, L.F. (1929) *Types of Farming in Minnesota*. Agricultural Experiment Station Bulletin Number 257. University of Minnesota. St. Paul, MN.

Grant, W.R. and R.D. Krenz (1985) *U. S. grain sorghum production practices and costs*. Staff Report No. AGES 851024. National Economics Division, Economics Research Service, U.S. Department of Agriculture.

Gurung, R.B., F.J. Breidt, A. Dutin, and S.M. Ogle (2009) Predicting Enhanced Vegetation Index (EVI) for ecosystem modeling applications. Remote Sensing of Environment 113:2186-2193.

Hargreaves, M.W.M. (1993) *Dry Farming in the Northern Great Plains: Years of Readjustment, 1920-1990*. University Press of Kansas. Lawrence, KS.

Hodges, J.A., F.F. Elliott, and W.E. Grimes (1930) *Types of Farming in Kansas*. Agricultural Experiment Station Bulletin Number 251. Kansas State Agricultural College. Manhattan, KS.

Holmes C.L. (1929) *Types of Farming in Iowa*. Agricultural Experiment Station Bulletin Number 259. Iowa State College of Agriculture and Mechanic Arts. Ames, IA.

Holmes G.K. (1902) "Practices in Crop Rotation." *Yearbook of the Department of Agriculture*, 519-532.

Hurd E.B. (1929) *The Corn Enterprise in Iowa*. Agricultural Experiment Station Bulletin Number 268. Iowa State College of Agriculture and Mechanic Arts. Ames, IA.

Hurd E.B. (1930) *Cropping Systems in Iowa Past and Present*. Agricultural Experiment Station Bulletin Number 268. Iowa State College of Agriculture and Mechanic Arts. Ames, IA.

Hurt, R.D. (1994) *American Agriculture: A Brief History*. Iowa State University Press. Ames, IA.

Ibach, D.B. and J.R. Adams (1967) *Fertilizer Use in the United States by Crops and Areas, 1964 Estimates*. Statistical Bulletin Number 408, U.S. Department of Agriculture.

Ibach, D.B., J.R. Adams, and E.I. Fox (1964) *Commercial Fertilizer used on Crops and Pasture in the United States, 1959 Estimates*. U.S. Department of Agriculture Statistical Bulletin Number 348.

ILENR (1993) *Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990*. Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

Iowa State College Staff Members (1946) *A Century of Farming in Iowa 1846-1946*. The Iowa State College Press. Ames, IA.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Jaynes, D.B., T.S. Colvin, D.L. Karlen, C.A. Cambardella, and D.W. Meek (2001) "Nitrate loss in subsurface draining as affected by nitrogen fertilizer rate." *J. Environ. Qual.* 30, 1305-1314.

Kellogg R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon (2000) *Manure Nutrients Relative to Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States*. U.S. Department of Agriculture Publication Number nps00-0579.

Kezer A. (ca. 1917) *Dry Farming in Colorado*. Colorado State Board of Immigration, Denver, CO.

Kuchler, AW. (1964) "The Potential Natural Vegetation of the Conterminous United States." *Amer. Geographical Soc. NY*, Special Publication No. 36.

Langston C.W., L.M. Davis, C.A. Juve, O.C. Stine, A.E. Wight, A.J. Pistor, and C.F. Langworthy (1922) "The Dairy Industry." *Yearbook of the Department of Agriculture*.

Latta, W.C. (1938) *Outline History of Indiana Agriculture*. Alpha Lambda Chapter of Epsilon Sigma Phi, Purdue University, West Lafayette, IN.

McCarl, B.A., C.C. Chang, J.D. Atwood, and W.I. Nayda (1993) *Documentation of ASM: The U.S. Agricultural Sector Model*, Technical Report TR-93. Agricultural Experimental Station, College Station, TX.

McFarland, M.J. (2001) *Biosolids Engineering*, New York: McGraw-Hill, p. 2.12.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. Bulletin of the American Meteorological Society 87:343-360.

Mosier, A.R. (2004) E-mail correspondence. Arvin Mosier, U.S. Department of Agriculture, Agricultural Research Service and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University, regarding the uncertainty in estimates of N application rates for specific crops (±20). September 20, 2004.

NASS (2004) *Agricultural Chemical Usage: 2003 Field Crops Summary*. Report AgCh1(04)a, National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdf>.

NASS (1999) *Agricultural Chemical Usage: 1998 Field Crops Summary*. Report AgCh1(99). National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf>.

NASS (1992) *Agricultural Chemical Usage: 1991 Field Crops Summary*. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txt>.

NEBRA (2007) *A National Biosolids Regulation, Quality, End Use & Disposal Survey*. North East Biosolids and Residuals Association, July 21, 2007

NFA (1946) "Charting the Fertilizer Course: Results of NFA's Third Practice Survey." National Fertilizer Association. *The Fertilizer Review*. Vol. XXI, 2:7-13.

Noller, J. (1996) Personal Communication. John Noller, Missouri Department of Natural Resources and Heike Mainhardt, ICF Incorporated. July 30, 1996.

NRAES (1992) *On-Farm Composting Handbook* (NRAES-54). Natural Resource, Agriculture, and Engineering Service. Available online at <http://compost.css.cornell.edu/OnFarmHandbook/onfarm_TOC.html>.

NRIAI (2003) Regional Budget and Cost Information. U.S. Department of Agriculture, Natural Resources Conservation Service, Natural Resources Inventory and Analysis Institute. Available online at <http://www.economics.nrcs.usda.gov/care/budgets/index.html>

Ogle, S.M., S. Del Grosso, W. Parton, S. Spencer and K. Paustian (In prep) Influence of soil management on greenhouse gas emissions in US agricultural lands from 1980 to 2007.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, and K. Paustian. (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration in Soils." *Ecological Modeling* 205:453-463.

Oregon Department of Energy (1995) *Report on Reducing Oregon's Greenhouse Gas Emissions: Appendix D Inventory and Technical Discussion.* Oregon Department of Energy. Salem, OR.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang*. 19: 35-48.

Parton, W.J., E.A. Holland, S.J. Del Grosso, M.D. Hartman, R.E. Martin, A.R. Mosier, D.S. Ojima, and D.S. Schimel (2001) Generalized model for NO_x and N_2O emissions from soils. *Journal of Geophysical Research*. 106 (D15):17403-17420.

Piper C.V., R.A. Oakley, H.N. Vinall, A.J. Pieters, W.J. Morse, W.J. Spillman, O.C. Stine, J.S. Cotton., G.A. Collier, M.R Cooper, E.C. Parker, E.W. Sheets, and A.T. Semple (1924) "Hay." *Yearbook of the Department of Agriculture*, 285-376.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster. (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. Earth Interactions 11, Article No. 13, DOI 10.1175/EI228.1.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) *County-level estimates of nutrient inputs to the land surface of* *the conterminous United States, 1982-2001*. Scientific Investigations Report 2006-5012. US Department of the Interior.

Ross W.H. and A.L. Mehring (1938) “Mixed Fertilizers.” In *Soils and Men*. Agricultural Yearbook 1938. U.S. Department of Agriculture.

Russell E.Z., S.S. Buckley, C.E. Baker, C.E. Gibbons, R.H. Wilcox, H.W. Hawthorne, S.W. Mendum, O.C. Stine, G.K. Holmes, A.V. Swarthout, W.B. Bell, G.S. Jamieson, C.W. Warburton, and C.F. Langworthy (1922) *Hog Production and Marketing*. Yearbook of the U.S. Department of Agriculture.

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick (1986) “Estimating Generalized Soil-Water Characteristics From Texture.” *Soil Sci. Soc. Am. J.* 50:1031-1036.

Skinner, J.J. (1931) *Fertilizers for Cotton Soils*. Miscellaneous Publication Number 126. U.S. Department of Agriculture.

Smalley, H.R., R.H. Engle, and H. Willett (1939) *American Fertilizer Practices: Second Survey*. The National Fertilizer Association.

Smith C.B. (1911) *Rotations in the Corn Belt*. Yearbook of the Department of Agriculture, pp.325-336.

Smith, P., J. Brenner, K. Paustian, G. Bluhm, J. Cipra, M. Easter, E.T. Elliott, K. Killian, D. Lamm, J. Schuler, and S. Williams (2002) *Quantifying the Change in Greenhouse Gas Emissions Due to Natural Resource Conservation Practice Application in Indiana*. Final Report to the Indiana Conservation Partnership, Colorado State University Natural Resource Ecology Laboratory and U.S. Department of Agriculture Natural Resources Conservation Service, Fort Collins, CO.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. (2005) *State Soil Geographic (STATSGO) Database for State*. Available online at <http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html>.

Spillman W.J. (1908) *Types of Farming in the United States*. Yearbook of the Department of Agriculture, 351-366.

Spillman W.J. (1907) *Cropping Systems for Stock Farms*. Yearbook of the Department of Agriculture, 385-398.

Spillman W.J. (1905) *Diversified Farming in the Cotton Belt*. Yearbook of the Department of Agriculture, 193-218.

Spillman W.J. (1902) *Systems of Farm Management in the United States*. Yearbook of the Department of Agriculture, 343-364.

Taylor, H.H. (1994) *Fertilizer Use and Price Statistics: 1960-93*. Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture, Statistical Bulletin Number 893.

Thornton, P.E., H. Hasenauer, and M.A. White (2000) “Simultaneous Estimation of Daily Solar Radiation and Humidity from Observed Temperature and Precipitation: An Application Over Complex Terrain in Austria.” *Agricultural and Forest Meteorology* 104:255-271.

Thornton, P.E. and S.W. Running (1999) “An Improved Algorithm for Estimating Incident Daily Solar Radiation from Measurements of Temperature, Humidity, and Precipitation.” *Agriculture and Forest Meteorology*. 93: 211-228.

Thornton, P.E., S.W. Running, and M.A. White (1997) “Generating Surfaces of Daily Meteorology Variables Over Large Regions of Complex Terrain.” *Journal of Hydrology.* 190:214-251.

TVA (1991 through 1992a, 1993 through 1994) *Commercial Fertilizers*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) *Fertilizer Summary Data 1992*. Tennessee Valley Authority, Muscle Shoals, AL.

USDA (2010a) *Crop Production 2009 Summary*, National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>,

USDA (2010b) Quick Stats: U.S. & All States Data - Crops. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, DC. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at <http://quickstats.nass.usda.gov/>

USDA (2003, 2005 through 2006, 2008 through 2009) *Crop Production Summary*, National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu>,

USDA (2000b) *Agricultural Statistics 2000*. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://www.usda.gov/nass/pubs/agstats.htm>.

USDA (1998) *Field Crops Final Estimates 1992-1997.* Statistical Bulletin Number 947a. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://usda.mannlib.cornell.edu>. Accessed July 2001.

USDA (1996) *Agricultural Waste Management Field Handbook*, *National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1994) *Field Crops: Final Estimates, 1987-1992*. Statistical Bulletin Number 896, National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, DC. Available online at <http://usda.mannlib.cornell.edu/data-sets/crops/94896/sb896.txt>.

USDA (1966) *Consumption of Commercial Fertilizers and Primary Plant Nutrients in the United States, 1850-1964 and By States, 1945-1964*. Statistical Bulletin Number 375, Statistical Reporting Service, U.S. Department of Agriculture.

USDA (1957) *Fertilizer Used on Crops and Pastures in the United States—1954 Estimates*. Statistical Bulletin Number 216, Agricultural Research Service, U.S. Department of Agriculture.

USDA (1954) *Fertilizer Use and Crop Yields in the United States*. Agricultural Handbook Number 68, the Fertilizer Work Group, U.S. Department of Agriculture.

USDA (1946) *Fertilizers and Lime in the United States*. Miscellaneous Publication Number 586, U.S. Department of Agriculture.

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at <http://www.ers.usda.gov/data/archive/93018/>.

USDA-ERS (2011) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Online at: http://ers.usda.gov/Data/ARMS/CropOverview.htm.

USDA-NRCS (2009) Summary Report: 2007 National Resources Inventory, Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa, http://www.nrcs.usda.gov/technical/NRI/2007/2007_NRI_Summary.pdf.

VEMAP (1995) Members (J.M. Melillo, J. Borchers, J. Chaney, H. Fisher, S. Fox, A. Haxeltine, A. Janetos, D.W. Kicklighter, T.G.F. Kittel, A.D. McGuire, R. McKeown, R. Neilson, R. Nemani, D.S. Ojima, T. Painter, Y. Pan, W.J. Parton, L. Pierce, L. Pitelka, C. Prentice, B. Rizzo, N.A. Rosenbloom, S. Running, D.S. Schimel, S. Sitch, T. Smith, I. Woodward). "Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): Comparing Biogeography and Biogeochemistry Models in a Continental-Scale Study of Terrestrial Ecosystem Responses to Climate Change and CO_2 Doubling." *Global Biogeochemical Cycles,* 9:407-437.

Vogelman, J.E., S.M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and J. N. Van Driel (2001) "Completion of the 1990's National Land Cover Data Set for the conterminous United States." *Photogrammetric Engineering and Remote Sensing,* 67:650-662.

Warren J.A. (1911) *Agriculture in the Central Part of the Semiarid Portion of the Great Plains*. Bulletin Number 215, Bureau of Plant Industry, U.S. Department of Agriculture.

Williams, S.A. (2006) Data compiled for the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS) from an unpublished manuscript. Natural Resource Ecology Laboratory, Colorado State University.

Wisconsin Department of Natural Resources (1993) *Wisconsin Greenhouse Gas Emissions: Estimates for 1990*. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

Field Burning of Agricultural Residues

Anderson, M. (2008 through 2011) Email correspondence. Monte Anderson, Oklahoma Farm Service Agency and

ICF International. July 12, 2010.

Ashman (2008). Email communication. Janet Ashman, Hawaii Agriculture Research Center and Victoria Thompson, ICF International. Ms. Ashman cited an August 2004 report prepared for the U.S. Dept. of Energy by the Hawaiian Commercial & Sugar Co., "Closed-Loop Biomass Co-Firing--Pilot-Scale and Full-Scale Test Results."

Barnard, G., and L. Kristoferson (1985) *Agricultural Residues as Fuel in the Third World*. Earthscan Energy Information Programme and the Beijer Institute of the Royal Swedish Academy of Sciences. London, England.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

Deren, C. (2002) Personal communication. Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

EPA (1994) *International Anthropogenic Methane Emissions: Estimates for 1990, Report to Congress.* EPA 230-R-93-010. Office of Policy Planning and Evaluation, U.S. Environmental Protection Agency, Washington, DC.

EPA (1992) *Prescribed Burning Background Document and Technical Information Document for Prescribed Burning Best Available Control Measures.* Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA-450/2-92-003.

Gonzalez, R. (2007 through 2011) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Guethle, D. (2007-2010) Email correspondence. David Guethle, Agronomy Specialist, Missouri Cooperative Extension Service and Sarah Menassian, ICF International. July 20, 2009.

Huang, Y., W. Zhang, W. Sun, and X. Zheng (2007) "Net Primary Production of Chinese Croplands from 1950 to 1999." *Ecological Applications*, 17(3):692-701.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, Montreal, IPCC-XVI/Doc. 10 (1.IV.2000). May 2000.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Jenkins, B.M., S.Q. Turn, and R.B. Williams (1992) “Atmospheric emissions from agricultural burning in California: determination of burn fractions, distribution factors, and crop specific contributions.” *Agriculture, Ecosystems and Environment* 38:313-330.

Kinoshita, C.M. (1988) "Composition and processing of burned and unburned cane in Hawaii." *Intl. Sugar Jnl.* 90:1070, 34-37.

Kirstein, A. (2003 through 2004) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, Florida and ICF International.

Lachnicht, S.L., P.F. Hendrix, R.L. Potter, D.C. Coleman, and D.A. Crossley Jr. (2004) "Winter decomposition of transgenic cotton residue in conventional-till and no-till systems." *Applied Soil Ecology*, 27:135-142.

Lee, D. (2003 through 2007) Email correspondence. Danny Lee, OK Farm Service Agency and ICF International.

McCarty, J.L. (2010) Agricultural Residue Burning in the Contiguous United States by Crop Type and State. Geographic Information Systems (GIS) Data provided to the EPA Climate Change Division by George Pouliot, Atmospheric Modeling and Analysis Division, EPA. Dr. McCarty’s research was supported by the NRI Air Quality Program of the Cooperative State Research, Education, and Extension Service, USDA, under Agreement No.

20063511216669 and the NASA Earth System Science Fellowship.

McCarty, J.L. (2009) *Seasonal and Interannual Variability of Emissions from Crop Residue Burning in the Contiguous United States*. Dissertation. University of Maryland, College Park.

Schueneman, T. (1999-2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International. July 30, 2001.

Schueneman, T.J. and C.W. Deren (2002) "An Overview of the Florida Rice Industry." SS-AGR-77, Agronomy Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Revised November 2002.

Strehler, A., and W. Stützle (1987) "Biomass Residues." In Hall, D.O. and Overend, R.P. (eds.) *Biomass*. John Wiley and Sons, Ltd. Chichester, UK.

Turn, S.Q., B.M. Jenkins, J.C. Chow, L.C. Pritchett, D. Campbell, T. Cahill, and S.A. Whalen (1997) "Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels." *Journal of Geophysical Research* 102(D3):3683-3699.

USDA (2011) Quick Stats: U.S. & All States Data; Crops; Production and Area Harvested; 1990 - 2010. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, DC. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at <http://quickstats.nass.usda.gov/>.

Walker, T. (2008) Email correspondence. Tim Walker, Assistant Research Professor, Mississippi State University Delta Branch Exp. Station and Sarah Menassian, ICF International. July 25, 2008.

Land Use, Land-Use Change, and Forestry

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

Representation of the U.S. Land Base

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. 2007. Completion of the 2001 National Land Cover Database for the Conterminous United States, Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

National Atlas (2005) *Federal Lands of the United States*. National Atlas of the United States, U.S. Department of the Interior, Washington DC. Available online at <http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound>.

Nusser, S.M. and J.J. Goebel (1997) "The national resources inventory: a long-term multi-resource monitoring programme." *Environmental and Ecological Statistics* 4:181-204.

Smith, W.B., P.D. Miles, C.H. Perry, and S.A. Pugh (2009) *Forest Resources of the United States, 2007*. Gen. Tech. Rep. WO-78. U.S. Department of Agriculture Forest Service, Washington, DC.

U.S. Census Bureau (2010) Topologically Integrated Geographic Encoding and Referencing (TIGER) system shapefiles. U.S. Census Bureau, Washington, DC. Available online at <http://www.census.gov/geo/www/tiger>.

Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks

AF&PA. 2006a (and earlier). Statistical roundup. (Monthly). Washington, DC: American Forest & Paper Association.

AF&PA. 2006b (and earlier). Statistics of paper, paperboard and wood pulp. Washington, DC: American Forest &

Paper Association.

Amichev, B. Y. and J. M. Galbraith (2004) "A Revised Methodology for Estimation of Forest Soil Carbon from Spatial Soils and Forest Inventory Data Sets." *Environmental Management* 33(Suppl. 1):S74-S86.

Barlaz, M.A. (1998) "Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills." *Global Biogeochemical Cycles* 12 (2):373-380.

Bechtold, W.A.; Patterson, P.L. 2005. The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station. 85 p.

Birdsey, R.A., and L.S. Heath (1995) "Carbon Changes in U.S. Forests." In *Productivity of America's Forests and Climate Change*. Gen. Tech. Rep. RM-271. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. Fort Collins, CO, 56-70.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds); *Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions*. American Forests. Washington, DC, 1-26 and 261-379 (appendices 262 and 263).

Birdsey, R., and L. S. Heath (2001) "Forest Inventory Data, Models, and Assumptions for Monitoring Carbon Flux." In *Soil Carbon Sequestration and the Greenhouse Effect*. Soil Science Society of America. Madison, WI, 125-135.

Birdsey, R. A., and G. M. Lewis (2003) "Current and Historical Trends in Use, Management, and Disturbance of U.S. Forestlands." In J. M. Kimble, L. S. Heath, R. A. Birdsey, and R. Lal, editors. *The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect*. CRC Press, New York, 15-34.

Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. *Carbon Balance and Management*. 6:14.

Eleazer, W.E., W.S. Odle, III, Y.S. Wang, and M.A. Barlaz (1997) "Biodegradability of municipal solid waste components in laboratory-scale landfills." *Env. Sci. Tech*. 31(3):911-917.

EPA (2010) *Inventory of U. S. Greenhouse Gas Emissions and Sinks: 1990–2008*. EPA, Office of Atmospheric Programs. Washington, DC.

EPA (2006) *Municipal solid waste in the United States: 2005 Facts and figures*. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, DC. (5306P) EPA530-R-06-011. Available online at <http://www.epa.gov/msw/msw99.htm>.

Frayer, W.E., and G.M. Furnival (1999) "Forest Survey Sampling Designs: A History." *Journal of Forestry* 97(12): 4-10.

Freed, R. (2004) Open-dump and Landfill timeline spreadsheet (unpublished). ICF International. Washington, DC.

Hair. D. and A.H. Ulrich (1963) The Demand and price situation for forest products – 1963. U.S. Department of Agriculture Forest Service, Misc Publication No. 953. Washington, DC.

Hair, D. (1958) "Historical forestry statistics of the United States." Statistical Bull. 228. U.S. Department of Agriculture Forest Service, Washington, DC.

Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.

Heath, L. (2007) Email communication between Kim Klunich, EPA, and Linda Heath, U.S. Forest Service. November 9, 2007.

Heath, L.S. (2006a) Email correspondence. Linda Heath, U.S. Department of Agriculture Forest Service and Kimberly Klunich, U.S. Environmental Protection Agency regarding the 95 percent CI for forest area estimates (± 0.24%) and average carbon density for Lower 48 States (± 0.4%). October 26, 2006.

Heath, L.S. (2006b) Email correspondence. Linda Heath, U.S. Department of Agriculture Forest Service and Kimberly Klunich, U.S. Environmental Protection Agency regarding the 95 percent CI for average carbon density for Alaska (±1.2%). October 27, 2006.

Heath, L.S., J.E., Smith, and R.A. Birdsey (2003) Carbon Trends in U. S. Forestlands: A Context for the Role of Soils in Forest Carbon Sequestration. In J. M. Kimble, L. S. Heath, R. A. Birdsey, and R. Lal, editors. *The Potential of U. S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect*. Lewis Publishers (CRC Press). Boca Raton, FL, 35-45.

Heath, L. S., and J.E. Smith (2000) "Soil Carbon Accounting and Assumptions for Forestry and Forest-related Land Use Change." In *The Impact of Climate Change on America's Forests*. Joyce, L.A., and Birdsey, R.A. Gen. Tech. Rep. RMRS-59. Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture. Fort Collins, CO, 89-101.

Heath, L. S., J. E. Smith, C. W. Woodall, D. L. Azuma, and K. L. Waddell (2011) Carbon stocks on forestlands of the United States, with emphasis on USDA Forest Service ownership. *Ecosphere* 2(1), article 6, 21 p.

Howard, James L. (2003) *U.S. timber production, trade, consumption, and price statistics 1965 to 2002*. Res. Pap. FPL-RP-615. Madison, WI: USDA, Forest Service, Forest Products Laboratory. Available online at <http://www.fpl.fs.fed.us/documnts/fplrp/fplrp615/fplrp615.pdf>.

Howard, James L. (2007) *U.S. timber production, trade, consumption, and price statistics 1965 to 2005*. Res. Pap. FPL-RP-637. Madison, WI: USDA, Forest Service, Forest Products Laboratory.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. Paris, France.

Jenkins, J,C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." *Forest Science* 49(1):12-35.

Johnson, D. W., and P. S. Curtis (2001) "Effects of Forest Management on Soil C and N Storage: Meta Analysis." *Forest Ecology and Management* 140:227-238.

Melosi, M. (2000) *The Sanitary City*. Johns Hopkins University Press. Baltimore, MD.

Melosi, M. (1981) *Garbage in The Cities: Refuse Reform and the Environment: 1880-1980*. Texas A&M Press.

Micales, J.A. and K.E. Skog (1997) "The decomposition of forest products in landfills." *International Biodeterioration & Biodegradation*. 39(2-3):145-158.

National Association of State Foresters (2007a) State Forestry Statistics 1998 Report. Available online at <http://www.stateforesters.org/statistics/FY98_Statistics/Resource%20Base.htm> March 2008.

National Association of State Foresters (2007b) State Forestry Statistics 2002 Report. Available online at <http://www.stateforesters.org/statistics/FY02_Statistics/2002%20Stat%20Resource%20Base.pdf> March 2008.

National Association of State Foresters (2007c) State Forestry Statistics 2004 Report. Available online at <http://www.stateforesters.org/statistics/FY04_Statistics/FY2004Statistics.pdf> March 2008.

Perry, C.H., C.W. Woodall, and M. Schoeneberger (2005) Inventorying trees in agricultural landscapes: towards an accounting of "working trees". In: "Moving Agroforestry into the Mainstream." *Proc. 9th N. Am. Agroforestry Conf.*, Brooks, K.N. and Ffolliott, P.F. (eds). 12-15 June 2005, Rochester, MN [CD-ROM]. Dept. of Forest Resources, Univ. Minnesota, St. Paul, MN, 12 p. Available online at <http://cinram.umn.edu/afta2005/> (verified 23 Sept 2006).

Phillips, D.L., S.L. Brown, P.E. Schroeder, and R.A. Birdsey (2000) "Toward Error Analysis of Large-Scale Forest Carbon Budgets." *Global Ecology and Biogeography* 9:305-313.

Skog, K.E., and G.A. Nicholson (1998) "Carbon Cycling Through Wood Products: The Role of Wood and Paper Products in Carbon Sequestration." *Forest Products Journal* 48:75-83.

Skog, K.E., K. Pingoud, and J.E. Smith (2004) "A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates." *Environmental Management* 33(Suppl. 1):S65-S73.

Skog, K.E. (2008) "Sequestration of carbon in harvested wood products for the United States." *Forest Products Journal* 58:56-72.

Smith, J.E., and L.S. Heath (2002) "A model of forest floor carbon mass for United States forest types." Res. Paper NE-722. USDA Forest Service, Northeastern Research Station, Newtown Square, PA.

Smith, J.E., and L.S.Heath (2010) "Exploring the assumed invariance of implied emission factors for forest biomass in greenhouse gas inventories." *Environmental Science & Policy* 13:55-62.

Smith, J. E., L. S. Heath, and J. C. Jenkins (2003) *Forest Volume-to-Biomass Models and Estimates of Mass for Live and Standing Dead Trees of U.S. Forests.* General Technical Report NE-298, USDA Forest Service, Northeastern Research Station, Newtown Square, PA.

Smith, J. E., L. S. Heath, and P. B. Woodbury (2004) "How to estimate forest carbon for large areas from inventory data." *Journal of Forestry* 102:25-31.

Smith, W. B., P. D. Miles, C. H. Perry, and S. A. Pugh (2009) *Forest Resources of the United States, 2007*. General Technical Report WO-78, U.S. Department of Agriculture Forest Service, Washington Office.

Smith, J.E., L.S. Heath, and M.C. Nichols (2010). U.S. Forest Carbon Calculation Tool User's Guide: Forestland Carbon Stocks and Net Annual Stock Change. General Technical Report NRS-13 revised, U.S. Department of Agriculture Forest Service, Northern Research Station, 34p..

Steer, Henry B. (1948) *Lumber production in the United States*. Misc. Pub. 669, U.S. Department of Agriculture Forest Service. Washington, DC.

Ulrich, Alice (1985) *U.S. Timber Production, Trade, Consumption, and Price Statistics 1950-1985*. Misc. Pub. 1453, U.S. Department of Agriculture Forest Service. Washington, DC.

Ulrich, A.H. (1989) *U.S. Timber Production, Trade, Consumption, and Price Statistics, 1950-1987*. USDA Miscellaneous Publication No. 1471, U.S. Department of Agriculture Forest Service. Washington, DC, 77.

USDC Bureau of Census (1976) *Historical Statistics of the United States, Colonial Times to 1970, Vol. 1*. Washington, DC.

USDA Forest Service (2011a) Forest Inventory and Analysis National Program: User Information. U.S. Department of Agriculture Forest Service. Washington, DC. Available online at <http://fia.fs.fed.us/tools-data/docs/default.asp>. Accessed 16 November 2011.

USDA Forest Service. (2011b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC. Available online at <http://apps.fs.fed.us/fiadb-downloads/datamart.html> Accessed 16 November 2011.

USDA Forest Service. (2011c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, DC. Available online at <http://www.fia.fs.fed.us/library/field-guides-methods-proc/>. Accessed 16 November 2011.

USDA Forest Service (2011d) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at < http://fia.fs.fed.us/library/database-documentation/ > Accessed 16 November 2011.

USDA Forest Service (2008) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at < http://www.fia.fs.fed.us/library/database-documentation/ >. Accessed 15 December 2009.

USDA Forest Service (1992) "1984-1990 Wildfire Statistics." Prepared by State and Private Forestry Fire and Aviation Management Staff. Facsimile from Helene Cleveland, USDA Forest Service, to ICF International. January 30, 2008.

USDA (1991) *State Soil Geographic (STATSG0) Data Base Data use information*. Miscellaneous Publication Number 1492, National Soil Survey Center, Natural Resources Conservation Service, U.S. Department of Agriculture, Fort Worth, TX.

Waddell, K., and B. Hiserote. 2005. The PNW-FIA Integrated Database User Guide: A database of forest inventory information for California, Oregon, and Washington. Forest Inventory and Analysis Program, Pacific Northwest Research Station, Portland, Oregon, USA.Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B, and Will-Wolf, S. (2011) "Status and future of the forest health indicators program of the USA" *Environmental Monitoring and Assessment*, 177:419-436.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols. (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., Domke, G.M., MacFarlane, D.W., Oswalt, C.M. (In Press) Comparing Field- and Model-Based Standing Dead Tree Carbon Stock Estimates Across Forests of the United States. *Forestry*.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B., Will-Wolf, S. (2011b) Status and future of the forest health indicators program of the United States. *Environmental Monitoring and Assessment*. 177: 419-436.

Woodbury, P.B., Heath, L.S., and Smith, J.E. (2006) "Land Use Change Effects on Forest Carbon Cycling Throughout the Southern United States." *Journal of Environmental Quality*, 35:1348-1363.

Woodbury, P.B., L.S. Heath, and J.E. Smith (2007) Effects of land use change on soil carbon cycling in the conterminous United States from 1900 to 2050, *Global Biogeochem. Cycles*, 21, GB3006, doi:10.1029/2007GB002950.

Woudenberg, S.W.; Conkling, B.L.; O'Connell, B.M.; LaPoint, E.B.; Turner, J.A.; Waddell, K.L. 2010. The Forest Inventory and Analysis Database: Database description and users manual version 4.0 for Phase 2. Gen. Tech. Rep. RMRS-GTR- 245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 339.

Forest Land Remaining Forest Land: Non-CO$_2$ Emissions from Forest Fires

Alaska Department of Natural Resources (2008) Division of Forestry. "Fire Statistics." Available online at <http://forestry.alaska.gov/firestats/> October 2008.

Alaska Interagency Coordination Center (AICC) (2011). "2010 Fire Season Statistics." Available online at <http://fire.ak.blm.gov/content/aicc/stats/2010.pdf>

Heath, L. (2008) Phone communication between Kim Klunich, EPA, and Linda Heath, U.S. Forest Service. November 24, 2008.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

National Association of State Foresters (1998) State Forestry Statistics 1998 Report. Available online at <http://www.stateforesters.org/files/1998ResourceBase.pdf > October 2008.

National Association of State Foresters (2002) State Forestry Statistics 2002 Report. Available online at <http://www.stateforesters.org/files/2002_20Stat_20Resource_20Base.pdf > October 2008.

National Association of State Foresters (2004) State Forestry Statistics 2004 Report. Available online at <http://www.stateforesters.org/files/FY2004Statistics.pdf > October 2008.

National Association of State Foresters (2008) State Forestry Statistics 2006 Report. Available online at <http://www.stateforesters.org/files/2006%20State%20Forestry%20Statistics-Web-Final.pdf> February 2009.

National Association of State Foresters (2011). State Forestry Statistics Spreadsheet. Available online at <http://www.stateforesters.org/publication-type/stats> November 2011.

National Interagency Fire Center (2011) "Fire Information—Wildland Fire Statistics. Total Wildland Fires and Acres (1960-2009)." Available online at <http://www.nifc.gov/fireInfo/fireInfo_statistics.html > November 2011.

Smith, J. (2008a) E-mail correspondence between Jean Kim, ICF, and Jim Smith, U.S. Forest Service, December 3, 2008.

Smith, J. (2008b) E-mail correspondence between Jean Kim, ICF, and Jim Smith, U.S. Forest Service, December 8, 2008.

Smith, J. (2008c) E-mail correspondence between Jean Kim, ICF, and Jim Smith, U.S. Forest Service, December 16, 2008.

Smith, J. (2009) E-mail correspondence between Jean Kim, ICF, and Jim Smith, U.S. Forest Service, January 30, 2009.

USDA Forest Service (2010a) Forest Inventory and Analysis National Program: User Information. U.S. Department of Agriculture Forest Service. Washington, DC. Available online at <http://fia.fs.fed.us/tools-data/docs/default.asp> Accessed 07 October 2010.

USDA Forest Service. (2010b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, DC. Available online at < http://199.128.173.17/fiadb4-downloads/datamart.html> Accessed 07 October 2010.

USDA Forest Service. (2010c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, DC. Available online at <http://www.fia.fs.fed.us/library/field-guides-methods-proc/> Accessed 07 October 2010.

USDA Forest Service (2010d) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at < http://fia.fs.fed.us/library/database-documentation/ > Accessed 07 October 2010.

USDA Forest Service (1992) "1984-1990 Wildfire Statistics." Prepared by State and Private Forestry Fire and Aviation Management Staff. Facsimile from Helene Cleveland, USDA Forest Service, to ICF International. January 30, 2008.

Forest Land Remaining Forest Land: N_2O Fluxes from Soils

Albaugh, T.J., Allen, H.L., Fox, T.R. (2007) Historical Patterns of Forest Fertilization in the Southeastern United States from 1969 to 2004. Southern Journal of Applied Forestry, 31, 129-137(9).

Binkley, D. (2004) Email correspondence regarding the 95% CI for area estimates of southern pine plantations receiving N fertilizer (±20%) and the rate applied for areas receiving N fertilizer (100 to 200 pounds/acre). Dan Binkley, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University. September 19, 2004.

Binkley, D., R. Carter, and H.L. Allen (1995) Nitrogen Fertilization Practices in Forestry. In: *Nitrogen Fertilization in the Environment*, P.E. Bacon (ed.), Marcel Decker, Inc., New York.

Briggs, D. (2007) *Management Practices on Pacific Northwest West-Side Industrial Forest Lands, 1991-2005: With Projections to 2010*. Stand Management Cooperative, SMC Working Paper Number 6, College of Forest Resources, University of Washington, Seattle.

Fox, T.R., H. L.Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson (2007) Tree Nutrition and Forest Fertilization of Pine Plantations in the Southern United States. Southern Journal of Applied Forestry. 31, 5-11.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

USDA Forest Service (2001) *U.S. Forest Facts and Historical Trends*. FS-696. U.S. Department of Agriculture Forest Service, Washington, DC. Available online at <http://www.fia.fs.fed.us/library/ForestFactsMetric.pdf>.

Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, and Land Converted to Grassland: Changes in Agricultural Soil Carbon Stocks

Allmaras, R.R., H.H. Schomberg, C.L. Douglas, Jr., and T.H. Dao (2000) "Soil organic carbon sequestration potential of adopting conservation tillage in U.S. croplands." *J Soil Water Conserv* 55:365–373.

Armentano, T.V. and J.T.A. Verhoeven (1990) "Biogeochemical Cycles: Global," in B.C. Patten, et al. (eds.); *Wetlands and Shallow Continental Water Bodies*. SPB Academic Publishing. The Hague, the Netherlands, Vol. I, 281-311.

Bastian, R. (2007) Personal Communication. Robert Bastian, Office of Water, U.S. Environmental Protection Agency, Washington, DC and Victoria Thompson, ICF International. July 20, 2007.

Brady, N.C. and R.R. Weil (1999) *The Nature and Properties of Soils*. Prentice Hall. Upper Saddle River, NJ, 881.

CTIC (1998) "1998 Crop Residue Management Executive Summary." Conservation Technology Information Center. West Lafayette, IN.

Daly, C., R.P. Neilson, and D.L. Phillips (1994) "A Statistical-Topographic Model for Mapping Climatological Precipitation Over Mountainous Terrain." *Journal of Applied Meteorology* 33:140-158.

Dean, W. E., and E. Gorham (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geology 26:535-538.

Easter, M. , S. Williams, and S. Ogle. (2008) Gap-filling NRI data for the Soil C Inventory. Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO. Report provided to the U.S. Environmental Protection Agency, Tom Wirth.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at <http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html>.

EPA (1999) *Biosolids Generation, Use and Disposal in the United States*. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at <http://biosolids.policy.net/relatives/18941.PDF>.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403, and 503.

ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at <http://www.ers.usda.gov/data/archive/93018/>.

ERS (1988) *Agricultural Resources—Inputs Situation and Outlook Report*. AR-9. Economic Research Service, U.S. Department of Agriculture.

Euliss, N., and R. Gleason (2002) Personal communication regarding wetland restoration factor estimates and restoration activity data. Ned Euliss and Robert Gleason of the U.S. Geological Survey, Jamestown, ND, to Stephen Ogle of the National Resource Ecology Laboratory, Fort Collins, CO. August 2002.

Eve, M. (2001) E-mail correspondence. Marlen Eve, Natural Resources Ecology Laboratory, Colorado State University and Barbara Braatz and Caren Mintz, ICF International. Statistics on U.S. organic soil areas cultivated in 1982, 1992, and 1997, which were extracted from the *1997 National Resources Inventory.* September 21, 2001.

Grant, W.R. and R.D. Krenz (1985) *U. S. grain sorghum production practices and costs*. Staff Report No. AGES 851024. National Economics Division, Economics Research Service, U.S. Department of Agriculture.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon (2000) *Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States*. U.S. Department of Agriculture, Washington, DC. Publication number nps00-0579.

McFarland, M.J. (2001) *Biosolids Engineering*, New York: McGraw-Hill, p. 2.12.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) “CENTURY Soil Organic Matter Model Environment.” Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

NASS (2004) *Agricultural Chemical Usage: 2003 Field Crops Summary*. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <Hhttp://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH>.

NASS (1999) *Agricultural Chemical Usage: 1998 Field Crops Summary*. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf>.

NASS (1992) *Agricultural Chemical Usage: 1991 Field Crops Summary*. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at <Hhttp://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH>.

NEBRA (2007) *A National Biosolids Regulation, Quality, End Use & Disposal Survey*. North East Biosolids and Residuals Association, July 21, 2007

NRAES (1992) *On-Farm Composting Handbook* (NRAES-54). Natural Resource, Agriculture, and Engineering Service. Available online at <http://compost.css.cornell.edu/OnFarmHandbook/onfarm_TOC.html>.

NRCS (1999) *Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition.* Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, DC.

NRCS (1997) “National Soil Survey Laboratory Characterization Data,” Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

NRCS (1981) *Land Resource Regions and Major Land Resource Areas of the United States*, USDA Agriculture Handbook 296, United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Cente., Lincoln, NE, pp. 156.

Nusser, S.M., J.J. Goebel (1997) The national resources inventory: a long term monitoring programme. *Environmental and Ecological Statistics*, **4**, 181-204.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2009) “Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model.” *Global Change Biology*, in press.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. (2007) “Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils.” *Ecological Modeling* 205:453-463.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) “Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments.” *Global Change Biology* 12:516-523.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) “Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997.” *Global Change Biology* 9:1521-1542.

Ogle, S., M. Eve, M. Sperrow, F.J. Breidt, and K. Paustian (2002) Agricultural Soil C Emissions, 1990-2001: Documentation to Accompany EPA Inventory Tables. Natural Resources Ecology Laboratory, Fort Collins, CO. Provided in an e-mail from Stephen Ogle, NREL to Barbara Braatz, ICF International. September 23, 2002

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) “Analysis of factors controlling soil organic matter levels in Great Plains grasslands.” *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) “Dynamics of C, N, P, and S in grassland soils: a model.” *Biogeochemistry* 5:109-131.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) “A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management,” in *Quantitative Modeling of Soil Forming Processes*. Special Publication 39, Soil Science Society of America, Madison, WI, 147-167.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster. (1993) “Terrestrial ecosystem production: a process model based on global satellite and surface data.” *Global Biogeochemical Cycles* 7:811-841.

Reilly, J.M. and K.O. Fuglie. (1998) “Future yield growth in field crops: What evidence exists?” *Soil Till Res* 47:275–290.

USDA-FSA (2007) Conservation Reserve Program Summary and Enrollment Statistics FY 2006. U.S. Department of Agriculture, Farm Service Agency, Washington, DC, Available online at http://www.fsa.usda.gov/Internet/FSA_File/06rpt.pdf.

USDA (1996) *Agricultural Waste Management Field Handbook*, *National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1966) *Consumption of Commercial Fertilizers and Primary Plant Nutrients in the United States, 1850-1964 and By States, 1945-1964*. Statistical Bulletin Number 375, Statistical Reporting Service, U.S. Department of Agriculture.

USDA (1957) *Fertilizer Used on Crops and Pastures in the United States—1954 Estimates*. Statistical Bulletin Number 216, Agricultural Research Service, U.S. Department of Agriculture.

USDA (1954) *Fertilizer Use and Crop Yields in the United States*. Agricultural Handbook Number 68, the Fertilizer Work Group, U.S. Department of Agriculture.

USDA-NRCS (2000) *Digital Data And Summary Report: 1997 National Resources Inventory*. Revised December 2000. Resources Inventory Division, Natural Resources Conservation Service, United States Department of Agriculture, Beltsville, MD.

Peatlands Remaining Peatlands: CO_2 and N_2O Emissions from Peatlands Remaining Peatlands

Apodaca, L. (2008) E-mail correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. October and November.

Apodaca, L. (2011). Email correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. November.

Cleary, J., N. Roulet and T.R. Moore (2005) “Greenhouse gas emissions from Canadian peat extraction, 1990-2000: A life-cycle analysis.” *Ambio* 34:456–461.

Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2011) *Alaska’s Mineral Industry Report (1997–2010).* Alaska Department of Natural Resources, Fairbanks, AK. Available online at <http://www.dggs.dnr.state.ak.us/pubs/pubs?reqtype=minerals>.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Szumigala, D.J. (2008). Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. October 17th, 2008.

Szumigala, D.J., R.A. Hughes and L.A. Harbo (2010) *Alaska's Mineral Industry 2009: A Summary.* Division of Geological & Geophysical Surveys, Alaska Department of Natural Resources, Fairbanks, AK. Available online at <http://www.dggs.alaska.gov/webpubs/dggs/ic/text/ic060.PDF>.

Szumigala, D.J. (2011). Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. January 18th, 2011.

United States Geological Survey (USGS) (1996–2011) *Mineral Commodity Summaries: Peat (1996–2010).* United States Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html#myb>.

United States Geological Survey (USGS) (1991–2011) *Minerals Yearbook: Peat (1994–2009).* United States Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html#myb>.

United States Geological Survey (USGS) (2011a) *Mineral Commodity Summaries 2011: Peat*. United States Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/peat/>.

United States Geological Survey (USGS) (2011b) *2009 Minerals Yearbook: Peat [Advance Release].* United States Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html#myb>.

Liming and Urea

AAPFCO (1995 through 2000a, 2002 through 2011b) *Commercial Fertilizers*. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

AAPFCO (2000b) *1999-2000 Commercial Fertilizers Data, ASCII files.* Available from David Terry, Secretary, AAPFCO.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Itle, Cortney (2009) Email correspondence. Cortney Itle, ERG and Tom Wirth, U.S. Environmental Protection Agency on the amount of urea used in aircraft deicing. January 7, 2009.

Tepordei, V. V. (1994) "Crushed Stone," In *Minerals Yearbook 1992*. U.S. Department of the Interior/Bureau of Mines, Washington, DC. pp. 1279-1303.

Tepordei, V.V. (1993) "Crushed Stone," In *Minerals Yearbook 1991*. U.S. Department of the Interior/Bureau of Mines, Washington, DC. pp. 1469-1511.

Tepordei, V.V. (1995) "Crushed Stone," In *Minerals Yearbook 1993*. U.S. Department of the Interior/Bureau of Mines, Washington, DC. pp. 1107–1147.

Tepordei, V.V. (1996) "Crushed Stone," In *Minerals Yearbook 1994*. U.S. Department of the Interior/Bureau of Mines, Washington, DC. Available online at http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2000.

Tepordei, V.V. (1997 through 2006) "Crushed Stone," In *Minerals Yearbook*. U.S. Department of the Interior/U.S. Geological Survey. Washington, DC. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

Tepordei, Valentin V. (2003b) Personal communication. Valentin Tepordei, U.S. Geological Survey and ICF Consulting, August 18, 2003.

Terry, D. (2007) Email correspondence. David Terry, Fertilizer Regulatory program, University of Kentucky and David Berv, ICF International. September 7, 2007.

TVA (1991 through 1994) *Commercial Fertilizers*. Tennessee Valley Authority, Muscle Shoals, AL.

U.S. EPA. (2000) Preliminary Data Summary: Airport Deicing Operations (Revised). EPA-821-R-00-016. August 2000.

USGS (2007) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2007*. U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2008) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2008*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2009) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2009*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2010) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2010*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

USGS (2011) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2011*, U.S. Geological Survey, Reston, VA. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.

West, T.O., and A.C. McBride (2005) "The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions," *Agricultural Ecosystems & Environment* 108:145-154.

West, Tristram O. (2008). Email correspondence. Tristram West, Environmental Sciences Division, Oak Ridge National Laboratory, U.S. Department of Energy and Nikhil Nadkarni, ICF International on suitability of liming emission factor for the entire United States. June 9, 2008.

Willett, J.C. (2007a) "Crushed Stone," In *Minerals Yearbook 2005*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2007.

Willett, J.C. (2007b) "Crushed Stone," In *Minerals Yearbook 2006*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2008.

Willett, J.C. (2009) "Crushed Stone," In *Minerals Yearbook 2007*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2009.

Willett, Jason C. (2010). "Crushed Stone," 2008 Minerals Yearbook. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2010.

Willett, J.C. (2010) "Crushed Stone," In *Minerals Yearbook 2009*. U.S. Department of the Interior/U.S. Geological Survey, Washington, DC. Available online at <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2011.

Settlements Remaining Settlements: N_2O Fluxes from Soils

Albaugh, T.J., Allen, H.L., Fox, T.R. (2007) *Historical Patterns of Forest Fertilization in the Southeastern United States from 1969 to 2004*. Southern Journal of Applied Forestry, 31, 129-137(9)

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) *County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001*. Scientific Investigations Report 2006-5012. U.S. Department of the Interior.

Settlements Remaining Settlements: Changes in Carbon Stocks in Urban Trees

Arthur, M. (2011) Phone conversation regarding U.S. Census Bureau information on urban areas and geography. Mike Arthur, U.S. Census Bureau, and Nick Devonshire, ICF International. October 6, 2011.

Cairns, M.A., S. Brown, E.H. Helmer, and G.A. Baumgardner (1997) "Root Biomass Allocation in the World's Upland Forests." *Oceologia* 111:1–11.

deVries, R.E. (1987) *A Preliminary Investigation of the Growth and Longevity of Trees in Central Park*. M.S. thesis, Rutgers University, New Brunswick, NJ.

Dwyer, J.F., D.J. Nowak, M.H. Noble, and S.M Sisinni (2000) *Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests*. General Technical Report PNW-GTR-490, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Fleming, L.E. (1988) *Growth Estimation of Street Trees in Central New Jersey*. M.S. thesis, Rutgers University, New Brunswick, NJ.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, E. Lapoint (2012, in preparation) *Carbon Storage and Sequestration by Trees in Urban and Community Areas of the United States.* USDA, Forest Service, Northeastern Research Station, Syracuse, NY.

Nowak, D.J. (2011a) Phone conference regarding Changes in Carbon Stocks in Urban Trees estimation methodology. David Nowak, USDA, Jennifer Jenkins, EPA, and Mark Flugge and Nikhil Nadkarni, ICF International. January 4, 2011.

Nowak, D.J. (2011b) Phone conference regarding Changes in Carbon Stocks in Urban Trees estimation methodology. David Nowak, USDA, Jennifer Jenkins, EPA, and Mark Flugge and Nick Devonshire, ICF International. November 28, 2011.

Nowak, D.J. (2009) E-mail correspondence regarding new data for Chicago's urban forest. David Nowak, USDA Forest Service to Nikhil Nadkarni, ICF International. October 7, 2009.

Nowak, D.J. (2007a) "New York City's Urban Forest." USDA Forest Service. Newtown Square, PA, February 2007.

Nowak, D.J. (2007b) Personal Communication. David Nowak, USDA Forest Service and Susan Asam, ICF International. September 25, 2007.

Nowak, D.J. (2007c) E-mail correspondence regarding revised sequestration values and standard errors for sequestration values. David Nowak, USDA Forest Service to Susan Asam, ICF International. October 31, 2007.

Nowak, D.J. (2002a) E-mail correspondence containing information on possible urban tree carbon and forest carbon overlap. David Nowak, USDA Forest Service to Barbara Braatz, ICF International. January 10, 2002.

Nowak, D.J. (2002b) E-mail correspondence regarding significant digits. David Nowak, USDA Forest Service to Barbara Braatz, ICF International. October 29, 2002.

Nowak, D.J. (1994) "Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest." In: *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*. E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.). General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (1986) "Silvics of an Urban Tree Species: Norway Maple (Acer platanoides L.)." M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J. and D.E. Crane (2002) "Carbon Storage and Sequestration by Urban Trees in the United States." *Environmental Pollution* 116(3):381–389.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) *Brooklyn's Urban Forest*. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., M.H. Noble, S.M. Sisinni, and J.F. Dwyer (2001) "Assessing the U.S. Urban Forest Resource." *Journal of Forestry* 99(3):37–42.

Nowak, D.J., J.T. Walton, L.G. Kaya, and J.F. Dwyer (2005) "The Increasing Influence of Urban Environments on U.S. Forest Management." *Journal of Forestry* 103(8):377–382.

Smith, W.B. and S.R. Shifley (1984) *Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois*. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

Other: Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

Barlaz, M.A. (2008) “Re: Corrections to Previously Published Carbon Storage Factors.” Memorandum to Randall Freed, ICF International. February 28, 2008.

Barlaz, M.A. (2005) “Decomposition of Leaves in Simulated Landfill.” Letter report to Randall Freed, ICF Consulting. June 29, 2005.

Barlaz, M.A. (1998) “Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills.” *Global Biogeochemical Cycles* 12:373–380.

Eleazer, W.E., W.S. Odle, Y. Wang, and M.A. Barlaz (1997) “Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills.” *Environmental Science Technology* 31:911–917.

EPA (2011) *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2010*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. Available online at <http://www.epa.gov/osw/nonhaz/municipal/msw99.htm>.

EPA (2006 through 2011) *Municipal Solid Waste in the United States: Facts and Figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. Available online at <http://www.epa.gov/osw/nonhaz/municipal/msw99.htm>.

EPA (2005) *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. Available online at < http://www.epa.gov/osw/nonhaz/municipal/pubs/msw03rpt.pdf>.

EPA (2005a) *Municipal Solid Waste in the United States: 2003 Data Tables*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. Available online at <http://www.epa.gov/osw/nonhaz/municipal/pubs/03data.pdf>.

EPA (2003) *Characterization of Municipal Solid Waste in the United States: 2001 Update.* (Draft.) U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

EPA (1999) *Characterization of Municipal Solid Waste in the United States: 1998 Update.* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman et al. (eds.). Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>.

Oshins, C. and D. Block (2000) “Feedstock Composition at Composting Sites.” *Biocycle* 41(9):31–34.

Schneider, S. (2007, 2008) E-mail correspondence. Shelly Schneider, Franklin Associates, A Division of ERG and Sarah Shapiro, ICF International.

Tchobanoglous, G., H. Theisen, and S.A. Vigil (1993) *Integrated Solid Waste Management, 1st edition*. McGraw-Hill, NY. Cited by Barlaz (1998).Barlaz, M.A. (2008) “Re: Corrections to Previously Published Carbon Storage Factors.” Memorandum to Randall Freed, ICF International. February 28, 2008.

Waste

Landfills

40 CFR Part 60, Subpart Cc (2005) Emission Guidelines and Compliance Times for Municipal Solid Waste

Landfills, 60.30c--60.36c, Code of Federal Regulations, Title 40. Available online at <http://www.access.gpo.gov/nara/cfr/waisidx_05/40cfr60_05.html>.

40 CFR Part 60, Subpart WWW (2005) Standards of Performance for Municipal Solid Waste Landfills, 60.750--60.759, Code of Federal Regulations, Title 40. Available online at <http://www.access.gpo.gov/nara/cfr/waisidx_05/40cfr60_05.html>.

Barlaz, M.A. (1998) "Carbon Storage During Biodegradation of Municipal Solid Waste Components in Laboratory-scale Landfills." *Global Biogeochemical Cycles*, 12(2): 373-380, June 1998.

Barlaz, M.A. (2006) "Forest Products Decomposition in Municipal Solid Waste Landfills." *Waste Management*, 26(4): 321-333.

BioCycle (2006) "15th Annual BioCycle Nationwide Survey: The State of Garbage in America" By P. Simmons, N. Goldstein, S. Kaufman, N. Goldstein, N. Themelis, and J. Thompson. *BioCycle.* April 2006.

BioCycle (2008) "The State of Garbage in America" By L. Arsova, R. Van Haaren, N. Goldstein, S. Kaufman, and N. Themelis. *BioCycle.* December 2008. Available online at < http://www.jgpress.com/archives/_free/001782.html>.

BioCycle (2010) "The State of Garbage in America" By L. Arsova, R. Van Haaren, N. Goldstein, S. Kaufman, and N. Themelis. *BioCycle.* December 2010. Available online at <http://www.jgpress.com/archives/_free/002191.html>.

Czepiel, P., B. Mosher, P. Crill, and R. Harriss (1996) "Quantifying the Effect of Oxidation on Landfill Methane Emissions." *Journal of Geophysical Research*, 101(D11):16721-16730.

EIA (2007) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2006). Available online at <ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/>.

EPA (1993) *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress*, U.S. Environmental Protection Agency, Office of Air and Radiation. Washington, DC. EPA/430-R-93-003. April 1993.

EPA (1988) *National Survey of Solid Waste (Municipal) Landfill Facilities*, U.S. Environmental Protection Agency. Washington, DC. EPA/530-SW-88-011. September 1988.

EPA (1998) *Compilation of Air Pollution Emission Factors, Publication AP-42*, Section 2.4 Municipal Solid Waste Landfills. November 1998.

EPA (2010) Municipal Solid Waste Generation, Recycling, and Disposal in the United States Detailed Tables and Figures for 2009. December 2010. Available online at <http://www.epa.gov/osw/nonhaz/municipal/pubs/msw2009rpt.pdf >.

EPA (2011) *Landfill Gas-to-Energy Project Database.* Landfill Methane and Outreach Program. July 2011.

ERG (2011). Production Data Supplied by ERG for 1990-2009 for Pulp and Paper, Fruits and Vegetables, and Meat. August.

ICF International (2009). Updating Component-specific, First-order Decay Rates Used in Estimating *Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills* (Deliverable under EPA Contract Number EP-W-07-068, Task Order 054, Task 03). Memorandum to M. Weitz (EPA), November 12, 2009.

IPCC (2003) *Good Practice Guidance for Land Use*, Land-Use Change and Forestry, The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, J. Penman, M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, and F. Wagner (eds.). Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Mancinelli, R. and C. McKay (1985) "Methane-Oxidizing Bacteria in Sanitary Landfills." *Proc. First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals*, Minneapolis, MN, 437-450. August.

Peer, R., S. Thorneloe, and D. Epperson (1993) “A Comparison of Methods for Estimating Global Methane Emissions from Landfills.” *Chemosphere*, 26(1-4):387-400.

RTI (2004) Documentation for Changes to the Methodology for the Inventory of Methane Emissions from Landfills. Memorandum to E. Scheehle (EPA), August 26, 2004.

RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum to R. Schmeltz (EPA), January 14, 2011.

Solid Waste Association of North America (SWANA) (1998) *Comparison of Models for Predicting Landfill Methane Recovery*. Publication No. GR-LG 0075. March 1998.

U.S. Bureau of Census (2010) International Database. August 2010. Available online at <http://www.census.gov/ipc/www/idb/>.

Wastewater Treatment

Ahn et al. (2010) N_2O Emissions from Activated Sludge Processes, 2008-2009: Results of a National Monitoring Survey in the United States. Environ. Sci. Technol. 44: 4505-4511.

Aguiar and Bartram (2008) Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. August 10, 2008.

Beecher et al. (2007) “A National Biosolids Regulation, Quality, End Use & Disposal Survey, Preliminary Report.” Northeast Biosolids and Residuals Association, April 14, 2007.

Benyahia, F., M. Abdulkarim, A. Embaby, and M. Rao. (2006) Refinery Wastewater Treatment: A true Technological Challenge. Presented at the Seventh Annual U.A.E. University Research Conference.

CARB (2007) Attachments C TO F - Supplemental Materials Document for Staff Report: Initial Statement of Reasons for Rulemaking, Mandatory Reporting of Greenhouse Gas Emissions Pursuant to the California Global Warming Solutions Act of 2006 (Assembly Bill 32), Attachment E: Technical Attachment on Development of Emissions Reporting Requirements for Oil Refineries and Hydrogen Plants. California Environmental Protection Agency Air Resources Board, dated October 19, 2007, http://www.arb.ca.gov/regact/2007/ghg2007/suppisor.pdf.

Donovan (1996) *Siting an Ethanol Plant in the Northeast*. C.T. Donovan Associates, Inc. Report presented to Northeast Regional Biomass Program (NRBP). (April). Available online at <http://www.nrbp.org/pdfs/pub09.pdf>. Accessed October 2006.

EIA. (2011) Energy Information Administration. U.S. Refinery and Blender Net Production of Crude Oil and Petroleum Products (Thousand Barrels). Available online at: http://tonto.eia.doe.gov/dnav/pet/hist/mttrpus1a.htm. Accessed: August 2011.

EPA (1974) *Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Apple, Citrus, and Potato Processing Segment of the Canned and Preserved Fruits and Vegetables Point Source Category*. Office of Water, U.S. Environmental Protection Agency, Washington, DC, EPA-440/1-74-027-a. March 1974.

EPA (1975) *Development Document for Interim Final and Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Fruits, Vegetables, and Specialties Segment of the Canned and Preserved Fruits and Vegetables Point Source Category*. United States Environmental Protection Agency, Office of Water. EPA-440/1-75-046. Washington DC, October 1975.

EPA (1992) *Clean Watersheds Needs Survey 1992 – Report to Congress.* Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, DC.

EPA (1993) *Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category*. EPA-821-R-93-019. Office of Water, U.S. Environmental Protection Agency. Washington, DC. October 1993.

EPA (1996) *1996 Clean Water Needs Survey Report to Congress. Assessment of Needs for Publicly Owned Wastewater Treatment Facilities, Correction of Combined Sewer Overflows, and Management of Storm Water and Nonpoint Source Pollution in the United States.* Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, DC. Available online at <http://www.epa.gov/owm/mtb/cwns/1996rtc/toc.htm>. Accessed

July 2007.

EPA (1997a) *Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment*. EPA-600/R-97-091. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency. Washington, DC,. September 1997.

EPA (1997b) *Supplemental Technical Development Document for Effluent Guidelines and Standards (Subparts B & E).* EPA-821-R-97-011. Office of Water, U.S. Environmental Protection Agency. Washington, DC. October 1997.

EPA (1998) "AP-42 Compilation of Air Pollutant Emission Factors." Chapter 2.4, Table 2.4-3, page 2.4-13. Available online at <http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf>.

EPA (1999) *Biosolids Generation, Use and Disposal in the United States*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, DC, EPA530-R-99-009. September 1999.

EPA (2000) *Clean Watersheds Needs Survey 2000 - Report to Congress*. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, DC. Available online at <http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm>. Accessed July 2007.

EPA (2002) *Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Meat and Poultry Products Industry Point Source Category (40 CFR 432)*. EPA-821-B-01-007. Office of Water, U.S. Environmental Protection Agency. Washington, DC,. January 2002.

EPA (2004a) *Clean Watersheds Needs Survey 2004 – Report to Congress*. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, DC.

EPA (2008) *Municipal Nutrient Removal Technologies Reference Document: Volume 2 – Appendices.* U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, DC.

ERG (2006) Memorandum: Assessment of Greenhouse Gas Emissions from Wastewater Treatment of U.S. Ethanol Production Wastewaters. Prepared for Melissa Weitz, EPA. 10 October 2006.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. (2004) *Recommended Standards for Wastewater Facilities (Ten-State Standards)*.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, Montreal, IPCC-XVI/Doc. 10 (1.IV.2000). May.

Leverenz, H.L., G. Tchobanoglous, and J.L. Darby (2010) "Evaluation of Greenhouse Gas Emissions from Septic Systems". Water Environment Research Foundation, Alexandria, VA.

Lockwood-Post (2002) Lockwood-Post's Directory of Pulp, Paper and Allied Trades, Miller-Freeman Publications. San Francisco, CA.

Merrick (1998) Wastewater Treatment Options for the Biomass-to-Ethanol Process. Report presented to National Renewable Energy Laboratory (NREL). Merrick & Company. Subcontract No. AXE-8-18020-01. October 22, 1998.

Metcalf & Eddy, Inc. (2003) *Wastewater Engineering: Treatment, Disposal and Reuse*, 4th ed. McGraw Hill Publishing.

Metcalf & Eddy, Inc. (1991) *Wastewater Engineering: Treatment, Disposal and Reuse*, 3rd ed. McGraw Hill Publishing.

Nemerow, N.L. and A. Dasgupta (1991) Industrial and Hazardous Waste Treatment. Van Nostrand Reinhold. NY. ISBN 0-442-31934-7.

NRBP (2001) Northeast Regional Biomass Program. *An Ethanol Production Guidebook for Northeast States*. Washington, D.C. (May 3). Available online at <http://www.nrbp.org/pdfs/pub26.pdf>. Accessed October 2006.

Paper 360◦ (2007) “U.S. production rises slightly in December.” March 2007. Available online at < http://www.thefreelibrary.com/U.S.+production+rises+slightly+in+December.(The+Pulse)-a0161909243>. Accessed June 2007.

Pulp and Paper (2006) "AF&PA projects more capacity losses this year, small gains in 2007-08." April 2006.

Pulp and Paper (2005) "U.S. paper/board production rises in 2004 to 91.47 million tons." April 2005.

Pulp and Paper (2003-2008) “Month in Statistics.” January 2003-September 2008.

Renewable Fuels Association (2011) Historic U.S. Fuel Ethanol Production. Available online at <http://www.ethanolrfa.org/pages/statistics>. Accessed August 2011.

Ruocco (2006a) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. “Capacity of Bio-Methanators (Dry Milling).” October 6, 2006.

Ruocco (2006b) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman ,ERG. “Capacity of Bio-Methanators (Wet Milling).” October 16, 2006.

Scheehle, E.A., and Doorn, M.R. (2001) “Improvements to the U.S. Wastewater Methane and Nitrous Oxide Emissions Estimate.” July 2001.

Timm, C.M. (1985) Water use, conservation and wastewater treatment alternatives for oil refineries in New Mexico. NMERDI-2-72-4628.

U.S. Census Bureau (2009) “American Housing Survey.” Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, and 2009 reports. Available online at <http://www.census.gov/hhes/www/housing/ahs/nationaldata.html>. Accessed August 2010.

U.S. Census Bureau (2011) International Database. Available online at <http://www.census.gov/ipc/www/idb/> and <http://www.census.gov/ipc/www/idbprint.html>. Accessed August 2011.

USDA (2009) Economic Research Service. U.S. Food Supply: Nutrients and Other Food Components, Per Capita Per Day. Washington DC. Available online at <http://www.ers.usda.gov/Data/FoodConsumption/spreadsheets/nutrients07.xls#Totals!a1>. Accessed August 2011.

USDA (2011) National Agricultural Statistics Service. Washington, DC. Available online at <http://www.nass.usda.gov/Publications/Ag_Statistics/index.asp> and <http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/>. Accessed August 2011.

USPoultry (2006) Email correspondence. John Starkey, USPOULTRY to D. Bartram, ERG. 30 August 2006.

White and Johnson (2003) White, P.J. and Johnson, L.A. Editors. Corn: Chemistry and Technology. 2nd ed. AACC Monograph Series. American Association of Cereal Chemists. St. Paul, MN.

World Bank (1999) *Pollution Prevention and Abatement Handbook 1998*, Toward Cleaner Production. The International Bank for Reconstruction and Development, The World Bank, Washington, DC. ISBN 0-8213-3638-X.

Composting

EPA (2010) *Municipal Solid Waste in the United States: 2009 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/osw/nonhaz/municipal/pubs/msw2009rpt.pdf>.

EPA (2009) *Municipal Solid Waste in the United States: 2008 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>.

EPA (2008) *Municipal Solid Waste in the United States: 2007 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC. Available online at <http://www.epa.gov/osw/nonhaz/municipal/pubs/msw07-rpt.pdf >.

Franklin Associates (1997) *Characterization of Municipal Solid Waste in the United States: 1996 Update*. Report prepared for the U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division by Franklin Associates, Ltd., Prairie Village, KS. EPA530-R-97-015. June 1997.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

U.S. Census Bureau (2011). Resident Population Data: Population Change. Available online at <http://2010.census.gov/2010census/data/apportionment-pop-text.php>.

Waste Sources of Indirect Greenhouse Gas Emissions

EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

EPA (2009). "1970 - 2008 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.